PROTOTYPING THE USE OF DISPERSION MODELS TO PREDICT GROUND CONCENTRATIONS DURING BURNING OF DEPLOYED MILITARY WASTE

THESIS

Val Oppenheimer, Captain, USAF

AFIT/GEM/ENV/12-M16

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THESIS

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Abstract

United States military forces in Iraq and Afghanistan have often used open burning of solid waste as a means to achieve volume reduction and to minimize vector borne illnesses. Assessing exposures to burn pit emissions has proven challenging, requiring significant numbers of personnel and sampling equipment. This study examined the use of three common dispersion models to determine the feasibility of using software modeling to predict short-range exposures to burn pit emissions, in lieu of sole reliance on ground sampling. Four open burn tests of municipal solid waste were conducted at Tooele Army Depot, Utah. Aerial samples were collected above the burns to determine emission factors for CO_2 and $PM_{2.5}$. Three atmospheric dispersion modeling software packages, ALOHA, HPAC, and HYSPLIT, were populated with the emission factors to determine how well they predicted ground concentrations of carbon dioxide (CO_2) and fine particulate matter ($PM_{2.5}$) at nearby monitoring stations. Results of this study show that ALOHA and HPAC did not accurately predict ground concentrations at the microscale resolution. HYSPLIT performed better than other models with more accurate predictions of CO_2 for two of the four days. This limited testing suggests that more robust ground sampling is necessary to improve assessment of model performance. Additionally, more frequent input of accurate weather data will likely improve the predictive power of these models.

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Val Oppenheimer

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PROTOTYPING THE USE OF DISPERSION MODELS TO PREDICT GROUND CONCENTRATIONS DURING BURNING OF DEPLOYED MILITARY WASTE

I. Introduction

Background

Open burning has become a significant topic since deployed members returning from various deployments are experiencing increased incidences of respiratory problems. For example, 14% of deployed personnel have reported various respiratory ailments compared to 10% who have not deployed (Smith, Wong, Smith, Boyko, & Gackstetter, 2009). In addition, 17% of the personnel having respiratory problems sought medical help. As a result, these ailments typically reduce operational efficiency in a combat environment (Sanders et al., 2005). It is also important to note that longer deployment lengths correlated with more reported respiratory symptoms (Smith, Wong, Smith, Boyko, & Gackstetter, 2009). However, it is still not known whether these symptoms are attributed to local environment or burn pit operations.

Some of the health problems experienced by military members returning from deployment include respiratory diseases, cardiovascular diseases, chronic multisymptom illness (CMI), lupus erythematosus, rheumatoid arthritis, and possible connections to birth defects. Some deployed members returning from deployments are attributing the cause of those ailments to burn pit operations rather than just being deployed to a particular region (The Armed Forces Health Surveillance Center, 2010).

Open burning can release harmful toxins into the air which can be inhaled by deployed personnel. Therefore, researchers have sampled smoke plumes from various open burns, sampled the ash left over from combustion of municipal solid waste (MSW)

and developed various methods to describe emission factors associated with some of the main toxins of concern such as dioxins (Gullett & Raghunathan, 1997). Various other studies have found that the recommended exposure levels are sometimes exceeded by burning trash at deployed locations with mixed results in regards to emission levels of particulate matter. Samples were examined from Iraq, Kuwait, Afghanistan, and other deployed locations with open source burning. These studies found that open source burning does contribute to elevated levels of particulate matter (PM), PM_{10} and $PM_{2.5}$, and other chemicals. In some cases, the 1-Year Military Exposure Guideline (MEG) values of 50 $\mu g/m^3$ for PM_{10} and 15 $\mu g/m^3$ for $PM_{2.5}$ were exceeded by a factor of 10, but it is difficult to determine how much burn pit smoke contributed to those levels (Engelbrecht, McDonald, Gillies, & Gertler, 2008). MEGs represent pollutant concentration values at which various illnesses begin to occur for continuous or instantaneous exposures (USACHPPM Technical Guide 230).

The United States Army Center for Health Promotion and Preventive Medicine (USACHPPM) conducted a sampling study in 2008 which indicated the presence of harmful pollutants such as dioxins, polyaromatic hydrocarbons, and volatile organic compounds (VOCs) in Iraq, but all pollutants except for PM were reportedly within acceptable ranges. The study also found that exposure levels from burn pit smoke typically do not exceed the 1-year MEG (Taylor, 2008). One of the main concerns associated with open source burning is the release of polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF), which can reach dangerous levels in people through bioaccumulation over time and cause future health problems. Some of

the problems associated with open burning can be attributed to the lack of guidance regarding open burning operations.

United States Central Command (CENTCOM) and its subordinate commands provided comprehensive guidance on managing and operating burn pits in 2009. The three main points of the CENTCOM guidance included: 1) the time of day the waste should be burned, 2) a list of items prohibited from burning, and 3) the requirement to monitor dioxins, polycyclic aromatic hydrocarbons (PAHs), VOC, carbon monoxide (CO), hexachlorobenzene, PM_{10}, and $PM_{2.5}$ at least once a year (Headquarters United States Central Command, 2009).

Prior to the guidance being implemented, solid waste was unsorted and many of the items in the waste, to include electronic waste, tires, treated wood, and many others that create toxins were burned. In addition, there was no accountability of the amount of these wastes being burned. A concern brought up by the Government Accountability Office (GAO) was that even after the CENTCOM guidance was released, the U.S. forces did not monitor burn pit emissions as required (Trimble, 2010).

Department of Defense (DoD) Instruction 4715.19, which was released in 2011, states that open burning will only be implemented as the last possible alternative. If burn pits must be used to destroy solid waste, the commanders of the Combatant Commands must submit justification packages to the Under Secretary of Defense for Acquisitions, Technology, and Logistics (USD AT&L) every 180 days for approval. The instruction also prohibits open pit burning of tires, treated wood, batteries, compressed gas cylinders, fuel containers and aerosol cans (unless purged), polychlorinated biphenyls, petroleum, oils and lubricant products (other than waste fuel for initial combustion), asbestos,

mercury, foam tent material and excessive quantities of plastics (DoD Instruction 4715.19, 2011). As an alternative to open burning, several bases are using technologies such as two-stage incinerators or burn boxes/air curtain destructors (ACDs) for waste combustion, but emission rates for ACDs have not been investigated in great detail to show any potential benefits in reducing health risk.

Problem Statement

It has been a challenge for DoD medical professionals to accurately document exposures to burn pits and ACDs while deployed. Many variables potentially affect exposures experienced by deployed personnel, including spatial and temporal ones. No definitive "smoking gun" exists which pinpoints the exact cause(s) of respiratory ailments seen in returning troops. Air sampling is labor-intensive and, arguably, cannot be continuously performed due to the equipment and manpower required. Complicating the above problems are the many sources of pollution (e.g., power plants, vehicles, local dust storms) in the Area of Responsibility (AOR) that serve as confounders.

The main objective of this research was to determine whether computer dispersion modeling is a suitable substitute for traditional ground-based sampling. For this research, three dispersion models were compared to traditional sample results from the burning of municipal solid waste at Tooele Army Depot, Utah.

Research Questions

1. How well does air dispersion software predict downwind dispersion?
2. Which air dispersion software is most useful to Bioenvironmental Engineering in a deployed environment?

Thesis Document Overview

This thesis is written in the "scholarly article format" in which a journal manuscript is the focus and accompanying chapters and appendices comprise the remainder of the thesis. This chapter, Chapter I, introduces the problem and resulting research. Chapter II presents the journal manuscript (for submission to the Journal of Environmental Health), additional results, analysis, and conclusions. Finally, Chapter III provides additional information of potential interest to the reader.

II. Scholarly Article

Prototyping the Use of Dispersion Models to Predict Ground Concentrations During Burning of Deployed Military Waste

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Abstract

United States military forces in Iraq and Afghanistan have often used open burning of solid waste as a means to achieve volume reduction and to minimize vector borne illnesses. Assessing exposures to burn pit emissions has proven challenging, requiring significant numbers of personnel and sampling equipment. This study examined the use of three common dispersion models to determine the feasibility of using software modeling to predict short-range exposures to burn pit emissions, in lieu of sole reliance on ground sampling. Four open burn tests of municipal solid waste were conducted at Tooele Army Depot, Utah. Aerial samples were collected above the burns to determine emission factors for CO_2 and $PM_{2.5}$. Three atmospheric dispersion modeling software packages, ALOHA, HPAC, and HYSPLIT, were populated with the emission factors to determine how well they predicted ground concentrations of carbon dioxide (CO_2) and fine particulate matter ($PM_{2.5}$) at nearby monitoring stations. Results of this study show that ALOHA and HPAC did not accurately predict ground concentrations at the microscale resolution. HYSPLIT performed better than other models with more accurate predictions of CO_2 for two of the four days. This limited testing suggests that more robust ground sampling is necessary to improve assessment of

model performance. Additionally, more frequent input of accurate weather data will likely improve the predictive power of these models.

Introduction

Since the beginning of the wars in Iraq and Afghanistan, disposal of deployed military waste has been a challenge. The lack of off-base disposal options, and the inherent security concerns with hauling waste off the base, forces the US military to find solutions within the fenceline. Technologies, such as incinerators and burn boxes, are used when available, but high waste generation rates require bases to resort to open burning. In addition, it is difficult and costly to sample source and exposure emissions from open burning of waste, therefore air dispersion models could provide a benefit over using systematic sampling in a deployed environment.

Open Burning

Open burning has become a significant topic since deployed members returning from various deployments are experiencing increased incidences of respiratory problems. For example, 14% of deployed personnel have reported various respiratory ailments compared to 10% who have not deployed (Smith, Wong, Smith, Boyko, & Gackstetter, 2009). In addition, 17% of the personnel having respiratory problems sought medical help. As a result, these ailments typically reduce operational efficiency in a combat environment (Sanders et al., 2005).

In the deployed environment, off-base disposal options are limited and hauling waste to disposal sites often presents a security risk. Limited numbers of disposal devices such as incinerators or burn boxes force continued reliance on open burning. Open burning normally does not occur under ideal conditions and typically emits

particulate matter (PM), carbon monoxide (CO), methane (CH_4) and other light hydrocarbons, volatile organic compounds (VOCs) such as benzene, and semi-volatile organic compounds (SVOCs) including polycyclic aromatic hydrocarbons (PAHs). Polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDDs/Fs) can be emitted as well (Lemieux et al., 2004).

Several studies have been conducted to measure emissions from open burning of solid waste (Gullett & Raghunathan, 1997; Gullett, Lemieux, Lutes, Winterrowd, & Winters, 2001; Gullett et al., 2010). Government contractors have taken air samples and conducted studies in Iraq, Kuwait, Afghanistan, and other deployed locations where open burning is prevalent. These studies show that open source burning contributes to elevated levels of particulate matter (PM_{10} and $PM_{2.5}$), and other pollutants. In some cases, the 1-Year Military Exposure Guideline (MEG) values of 50 $\mu g/m^3$ for PM_{10} and the MEG of 15 $\mu g/m^3$ for $PM_{2.5}$ were exceeded by a factor of 10 times. However, it is not conclusive how much burn pit emissions contributed to those levels (Engelbrecht et al., 2008). CO_2, a surrogate of plume behavior, and $PM_{2.5}$, known as a causative agent of respiratory illness, were chosen to see how the models perform for gas dispersion and particle scenarios, respectively.

Atmospheric Dispersion Models

There are numerous air dispersion modeling software solutions that are used to predict downwind pollutant concentration. ALOHA (Areal Locations of Hazardous Atmospheres), HPAC (Hazard Prediction Capability), and HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) are models developed by government agencies

and are free to use. These models were selected for this study based on reasons described below.

The ALOHA model was developed by the National Oceanic and Atmospheric Administration (NOAA) and the Environmental Protection Agency (EPA) and uses a Gaussian approach to predict downwind dispersion of a chemical cloud (U.S. Environmental Protection Agency & National Oceanic and Atmospheric Administration, 2007). ALOHA is known for its ease of use and extensive database, which contains approximately 1,000 common hazardous chemicals. It is used to model toxicity, flammability, thermal radiation, and overpressure due to various chemical releases, explosions, and/or fires. The software's main limitation is that it can only model gas dispersion.

HPAC, developed by the Defense Threat Reduction Agency (DTRA), is known for its ability to model both gas and particle dispersion and can provide multiple output options (e.g., graphical, text). It is often used to model hazardous nuclear, biological, and chemical releases and to help predict fatalities from such releases. HPAC can model gas, particle, aerosol, or liquid releases. It uses SCIPUFF, which is an advanced Lagrangian, Gaussian puff model. HPAC uses internal terrain data, land cover data, and user defined or internal historic weather data to model dispersion. Dispersion run times depend on the weather data and source release duration (Defense Threat Reduction Agency, 2005).

HYSPLIT was developed by the National Oceanic and Atmospheric Administration (NOAA). It can model both gas and particle dispersion and uses Gaussian puff, particle dispersion, or both to model downwind concentrations.

Dispersion modeling times vary with the weather data used, source release duration, and dispersion type (Draxler & Hess, 1998).

Each model requires slightly different weather inputs to model dispersion. ALOHA uses single-point user-entered data, including wind speed and direction, ground roughness, cloud cover, air temperature, inversion if present, and humidity. HPAC uses gridded weather data, which can be downloaded or the user can enter weather data, including altitude, date and time, humidity, temperature, mixing height, stability, wind speed/direction, and other parameters. HYSPLIT weather data can be downloaded from Air Resource Laboratory (ARL) or the user can enter limited data.

Weather data comes in various resolutions, such as GFS (global low resolution) and NAM (North American high-resolution) with wind speeds, temperature, and humidity at various elevations and times. The resolution ranges from 2.5 degrees for global data to 12 km resolution for the North American Model data, while the timescale ranges from 12 hrs to 1 hr for each data point. For HYSPLIT, the user can also enter basic weather data manually, which is gridded to a 50 by 50 km domain for a short-range dispersion run. Only six data time points can be entered at one time or 6 hours' worth of data for a specific location.

Other models like CALPUFF, AERMOD, OBODM, and others were not selected as they require extensive training to use properly and would not be practical solutions in the deployed environment. Models without graphical user interfaces were also excluded, due to complicated setup procedures, as were models with license fees. Computational fluid dynamics (CFD) models, although very powerful, are considered too complex for deployed military scenarios.

Methods

Burn Testing

Four open surface burn tests were conducted at Tooele Army Depot (TEAD), Tooele County, Utah. Municipal solid waste was delivered to the site and windrows of waste approximately 70'x10'x3' were constructed, similar to how waste is normally burned in the deployed environment. Table 1 contains the approximate volume and weight of the waste burned each day.

Table 1: Summary of four open burn tests

Date	Approximate Weight (tons)	Volume (m^3)
30-Sep-11	5	35
1-0ct-11	8	56
2-0ct-11	6.5	45
3-0ct-11	6.3	44

Samples Collected

For this research, both ground-based and aerial samples were taken. Aerial samples were collected using an assembled instrument package, called the "Flyer," hoisted above the burn pile by either a crane, extendable forklift, and/or tethered aerostat balloon. Two Flyer packages were used to collect CO_2 and $PM_{2.5}$ data simultaneously during the open burn days and were repositioned as necessary based on wind conditions and plume behavior. CO_2 was measured using a LI-820 gas analyzer (LI-COR Biosciences, Lincoln NE) and $PM_{2.5}$ was sampled using a DustTrak (TSI Inc., Shoreview MN).

Three ground-based sampling stations were positioned in the prevailing downwind direction, at distances of approximately 40m, 60m, and 80m from the burn site. Each station used LI-820 and DustTrak instruments. Figure 1 shows simultaneous

sampling using the tethered aerostat, crane, extendable forklift, and ground-based sampling. Figure 2 shows the locations of ground samples for each open burn days.

Figure 1: Simultaneous sampling using aerostat, crane, forklift, and ground-based sampling devices

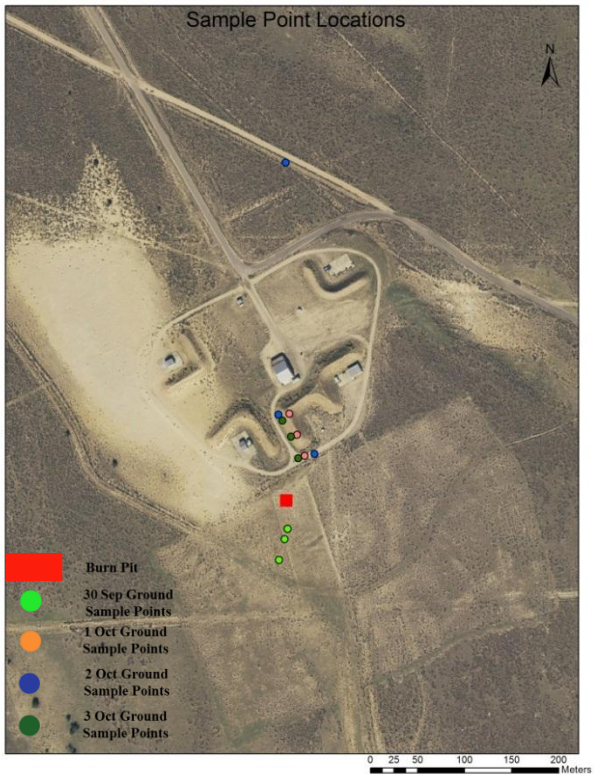

Figure 2: Ground Sample Locations

Emission Factors

Emission factors were calculated for each of the burn days. First, the volume of the waste pile was determined based on the mass of the waste material density prior to combustion (Tchobanoglous, Theisen, & Eliassen, 1977). Second, the mass of the waste pile and amount of carbon per specific waste component were used to determine the total amount of carbon in each waste pile (Pipatti, Sharma, & Yamada, 2006). Third, the emission time was estimated based on visual observation of the pile, which showed that the initial flaming phase ended around the one to two hour mark. Sampling was stopped when CO_2 levels returned near ambient levels.

After completion of the burns, ash volume was estimated and total mass loss was determined. Real time CO_2 and $PM_{2.5}$ data were taken every second. From the real time data, $PM_{2.5}$ to carbon ratio was determined for each second of collection. This ratio was multiplied by the carbon emission rate per second, to determine the $PM_{2.5}$ emission per second in mass per time, which was used in the models as the source emission rate.

Burn rates of carbon were estimated based on volume reduction of the waste during the $PM_{2.5}$ and CO_2 sampling times and using estimates of 130 kg/m^3 density of solid waste and 297 kg/m^3 density of ash (Tchobanoglous, Theisen, & Eliassen, 1977). The amount of carbon burned was determined by subtracting the final mass of the ash from the initial mass of the waste. It was assumed that most of the carbon emission happened during the sampling times, which consisted of an initial flaming phase followed by a smoldering phase. Flames died down anywhere from one to two hour mark after the start of the burn, after which smoldering conditions prevailed. Sampling was stopped after the flaming phase as CO_2 returned to near-background levels.

Software Modeling

ALOHA, HPAC, and HYSPLIT simulations were performed for both CO_2 and $PM_{2.5}$. Local surface weather data were collected every minute and included wind speed, direction, temperature, and humidity close to the open burning location. The data were averaged every hour for input into the models to reduce the number of dispersion runs. In addition to using surface weather (SW) data, HYSPLIT was also run with daily downloaded NAM weather (DW) data using a 12 km grid and 1 hr time scale. Concentration contours were plotted to show plume dispersion behavior at the Tooele Army Depot site.

Model Comparison

Ground data were compared to predicted point values from the dispersion models using statistical tests. Five common statistical tests performed were fractional bias (FB), geometric mean bias (MG), normalized mean square error (NMSE), geometric variance (VG), and fraction of predictions with a factor of two (FAC2) (Hanna, Egan, Purdum, & Wagler, 2001). For a model to be considered acceptable, FB would range from -0.67 to 0.67, MG would range from 0.5 to 2.0, VG from 0.75 to 1.6, NMSE less than 4, and FAC2 between 0.5 and 2.0 (Chang, Hanna, Boybeyi, & Franzese, 2010). An ideal model would have MG = VG = 1 and/or FB = NMSE = 0. Table 2 summarizes the typical model criteria. Further details on these statistical tests are found in the literature (Hanna, Egan, Purdum, & Wagler, 2001).

Table 2: Required Model Criteria

	Acceptable	Ideal
FB	$-0.67 \leq x \leq 0.67$	0.0
MG	$0.5 \leq x \leq 2.0$	1.0
NMSE	$0.0 \leq x \leq 4.0$	0.0
VG	$0.5 \leq x$ 2.0	1.0
FAC2	$0.75 \leq x$ 2.0	1.0

Results and Discussion

Emission Factors

The emission factors used in the models are shown in Table 3. Emission rates for CO_2 ranged from 992 kg/hr to 1570 kg/hr, where the rates for $PM_{2.5}$ ranged from 5.8 kg/hr to 27 kg/hr during the four days of sampling and were determined based on the carbon burned over time. The $PM_{2.5}$ emission factor ranged from 0.01 to 0.1 kg of $PM_{2.5}$ per kg of carbon with an average of 0.06 kg/kg carbon.

Table 3: Emission Factors

	CO_2 (kg/hr)	$PM_{2.5}$ (kg/hr)	Carbon Burned (kg)
30-Sep	992	14.7	825
1-Oct	1570	44.7	1283
2-Oct	1470	5.88	1226
3-Oct	1220	27.9	998

Ground Sampling and Modeling Results

Ground sampling results for CO_2 and $PM_{2.5}$ are shown in Table 4. The abbreviations S, M, and L (short, medium, long) represent the three ground stations placed at increasing distances away from the open burn (i.e., 40-100 m). Samples were taken each second for approximately three hours each day, during the period of flaming combustion and elevated CO_2. The large standard deviations indicate great variability in the ground sampling data collected, presumably due to changes in wind speed and direction during the tests.

Table 4: Ground Sampling Results

		Min CO_2 (mg/m^3)	Avg CO_2 (mg/m^3)	Max CO_2 (mg/m^3)	σ	Min $PM_{2.5}$ (mg/m^3)	Avg $PM_{2.5}$ (mg/m^3)	Max $PM_{2.5}$ (mg/m^3)	σ
30-Sep	S	0	39	1269	43	0	0.264	43.000	1.63
	M	0	21	509	17	0	0.083	15.462	0.53
	L	0	15	301	10	0	0.057	14.025	0.38
1-Oct	S	0	82	1994	165	0	4.442	149.938	9.83
	M	0	49	1071	62	0	4.819	71.702	9.97
	L	0	18	560	36	0	2.066	40.617	4.52
2-Oct	S	0	30	1844	101	0	0.170	11.756	0.69
	M	0	24	428	22	0	0.016	1.053	0.07
	L	0	10	511	38	0	0.113	5.912	0.44
3-Oct	S	0	228	1990	457	0	5.007	111.877	11.3
	M	0	94	2006	185	0	2.804	74.383	7.90
	L	0	66	1093	105	0	1.408	28.874	3.79

ALOHA, HPAC, and HYSPLIT models were run for all four days, using surface weather data collected at the site. ALOHA can predict ground concentration for a maximum of one hour of continuous emission. To get the average over the ground sampling period (approximately 3 hours) the model had to be used three times for each day. HYSPLIT was also run with the downloaded (DW) data for each of the four days.

Figures 3 through 6 show the graphical output for 30 September 2011 dispersion runs of CO_2 results over a 3-hour averaging time. Results for other days show similar patterns but are not shown here. For HYSPLIT using surface weather data (SW), a noticeable gap between the plume and the open burn (source location) indicates that this model may not adequately show concentrations on the microscale level as a region of zero concentration is indicated and contradicts non-zero ground sample results. HYSPLIT and ALOHA show 10 mg/m^3 (red), 5 mg/m^3 (orange), 1 mg/m^3 (yellow) CO_2

contours in figures 3-5. ALOHA outmost contour shows the 95 percent probability of the plume location. Figure 5 shows HPAC CO_2 contours that predicted very small concentration values therefore other values were chosen to represent the contours. The values are 0.001 to 0.01 mg/m^3 (green), 0.01 to 0.1 mg/m^3 (yellow), and 0.1 to 0.2 mg/m^3 (red).

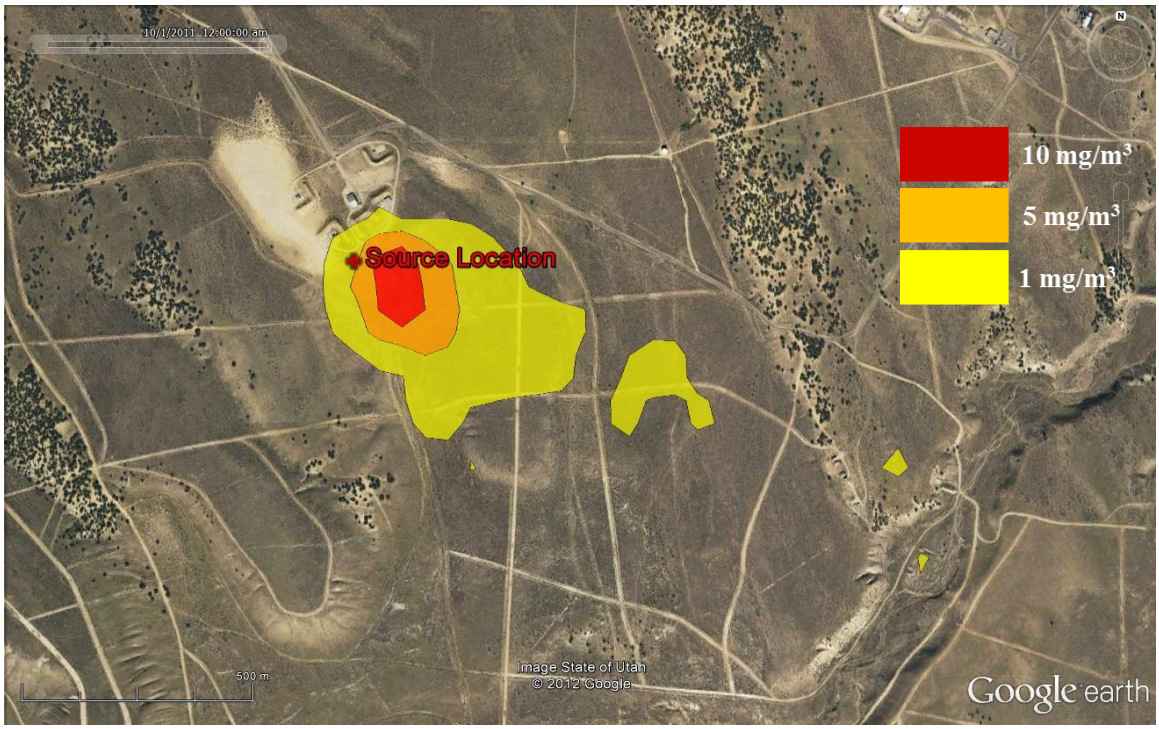

Figure 3: 30 Sep CO_2 HYSPLIT Contours Using NAM data

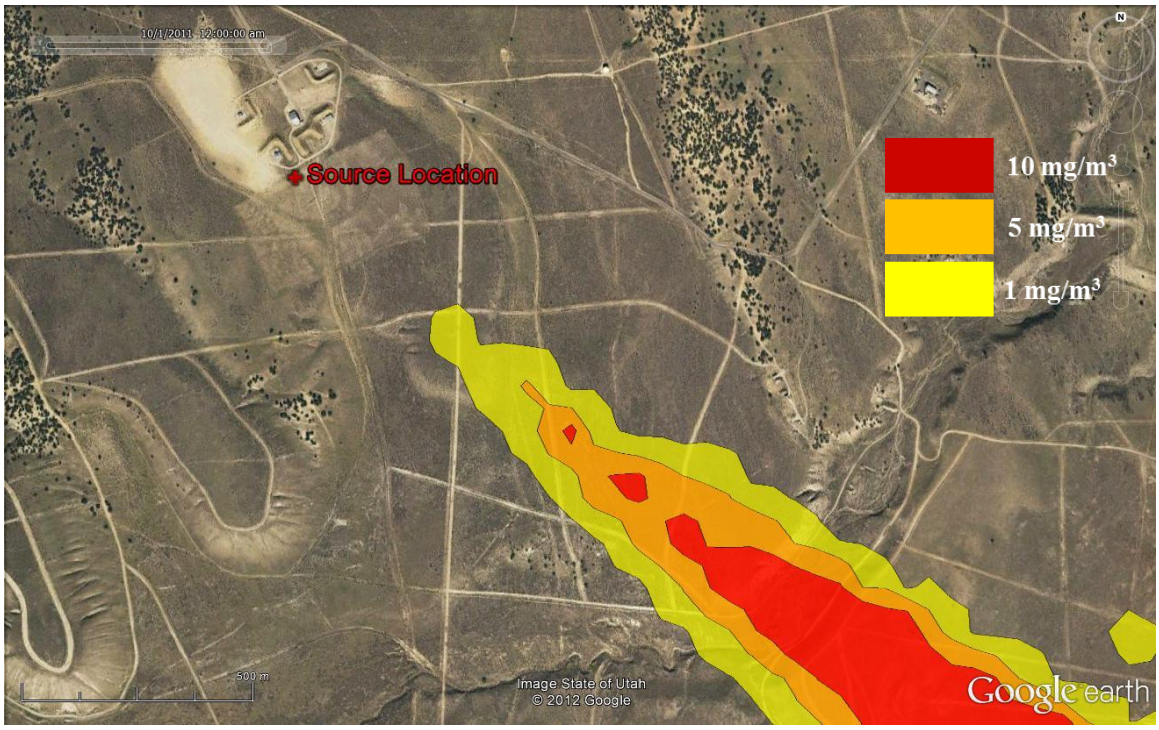

Figure 4: 30 Sep CO_2 HYSPLIT Contours Using Surface Weather

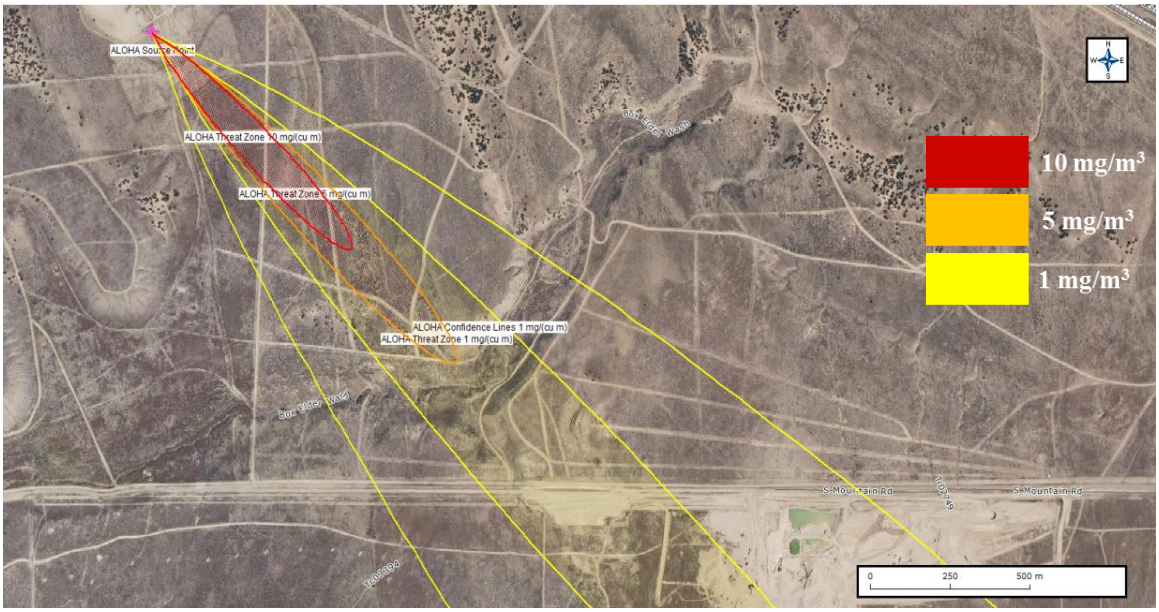

Figure 5: 30 Sep CO_2 ALOHA Contours Using Surface Weather

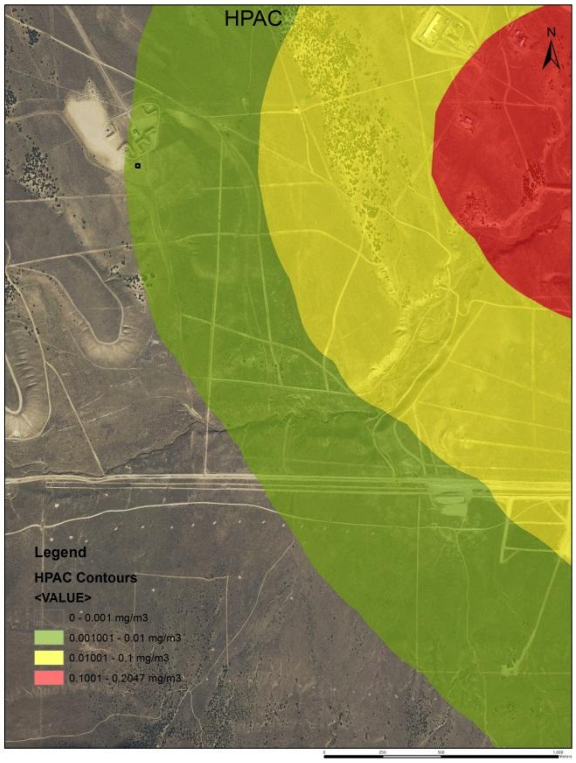

Figure 6: 30 Sep CO_2 HPAC Contours Using Surface Weather

To quantify how well the models predict true ground sample results, the five statistical tests described previously were performed. Table 5 shows the approach to assimilate these results, using simple green/yellow/red criteria to summarize model performance in predicting ground concentrations. Note that ALOHA does not accommodate particulate matter, so $PM_{2.5}$ does not appear in Table 5. ALOHA performance for this research was marginal, but it should be note that wind direction varied greatly during the four open burn tests. Therefore, using 1 hr averaged weather data, versus shorter time periods, is a likely reason why the model disagreed with ground sample results.

Table 5: ALOHA Statistical Results

Pollutant	Date	Performance
CO_2	30 Sep	Red
	1 Oct	Yellow
	2 Oct	Red
	3 Oct	Yellow

Green: Satisfies ≥ 3 of 5 statistical tests, for 2-3 ground stations
Yellow: Satisfies ≥ 3 of 5 statistical tests, for 1 ground station
Red: Does not meet above criteria

As shown in Table 6, HPAC also did not accurately predict ground concentration values for either $PM_{2.5}$ or for CO_2. The model generally predicted extremely small values for most open burn days at ground sampling locations and was not within the statistical values required for an acceptable model for the four testing days.

Table 6: HPAC Statistical Results

Pollutant	Date	Performance
CO_2	30 Sep	Red
	1 Oct	Red
	2 Oct	Red
	3 Oct	Red
$PM_{2.5}$	30 Sep	Red
	1 Oct	Red
	2 Oct	Red
	3 Oct	Red

Green: Satisfies ≥ 3 of 5 statistical tests, for 2-3 ground stations
Yellow: Satisfies ≥ 3 of 5 statistical tests, for 1 ground station
Red: Does not meet above criteria

HYSPLIT also performed poorly with user-entered hourly surface weather data (SW). However, downloaded NAM weather model data, DW, which is gridded on a 12 km by 12km domain with 1hr time resolution, resulted in better predictions of CO_2 concentrations for three out of the four open burn days. $PM_{2.5}$ was predicted only for one the four open burn days, using DW. Table 7 summarizes the HYSPLIT performance

using both SW and DW data. These tests, although limited in number, indicate that use of higher resolution DW data may provide better predictions of ground concentrations.

Table 7: HYSPLIT Statistical Results

Pollutant	Weather Data Source	Date	Performance
CO_2	SW	30 Sep	Red
		1 Oct	Red
		2 Oct	Red
		3 Oct	Red
	DW	30 Sep	Green
		1 Oct	Green
		2 Oct	Yellow
		3 Oct	Red
$PM_{2.5}$	SW	30 Sep	Red
		1 Oct	Red
		2 Oct	Red
		3 Oct	Red
	DW	30 Sep	Yellow
		1 Oct	Red
		2 Oct	Red
		3 Oct	Red

Green: Satisfies ≥ 3 of 5 statistical tests, for 2-3 ground stations
Yellow: Satisfies ≥ 3 of 5 statistical tests, for 1 ground station
Red: Does not meet above criteria

The main reason why the models performed poorly in predicting the ground concentrations was likely linked to the highly variable weather conditions (e.g., wind direction and speed) and use of a one-hour averaging time. Figure 3 shows wind rose data for each day and the wind direction variability supports the finding that one-hour averaging times may not be sufficient.

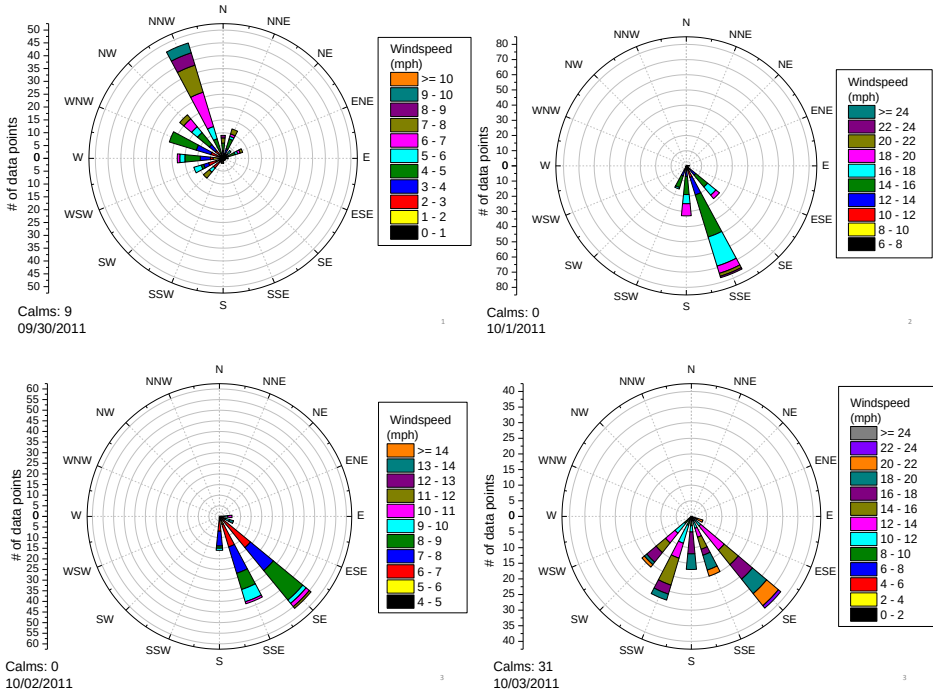

Figure 7: 30 Sep (Top Left), 1 Oct (Top Right), 2 Oct (Bottom Left), 3 Oct (Bottom Right) Wind Rose (courtesy of US EPA)

A second reason why the models may not have predicted ground concentrations very well was due to the relatively short sampling time. If sampling was continued over the 24 hour period, momentary spikes in ground concentration outliers would have less influence over a longer averaging period. Therefore, if samples were taken over a longer period of time, the ground concentration values would be lower and close to the model estimates. Due to wind direction variability, the ground monitoring stations only sampled open burn emissions only when the plume passed over them. A third reason why the models were not predictive is that there were only three ground stations and they were relatively close to the source. The closest station was 40 meters away and the furthest was only 100 meters away. Another reason why the models did not predict ground concentration values was that the stations were also set up parallel to the wind direction

at the start of the burn each day and were not adjusted for the duration of the burn. If the stations were positioned perpendicular to the wind direction, there is greater chance that the model would at least have predicted one of those points compared to none.

Model Improvements

There are numerous ways to improve the models for future use. One way is to use shorter averaging weather times. For all four sampling days, wind direction and speed varied greatly; therefore, using half an hour or even shorter average wind speed and direction should improve the model predictions. Currently, models use mesoscale resolution, which tends to do well for regional cases but might not do well for modeling dispersion in a local area where terrain features play a larger role. Therefore, microscale models should be investigated to see if they produce better results.

One common limitation of models is that source output (i.e., emission rate) cannot vary with time. However, combustion-related emission rates vary with time, e.g., the flaming phase consumes approximately 90% of combustible mass while smoldering consumes 10% (Akagi et al., 2010; de Zarate, Ezcurra, Lacaux, & Van Dinh, 2000). A possible improvement to these models would be to vary the source emission values for each time step.

Another improvement would be to vary plume rise according to the weather data for each time step. Plume rise mainly depends on temperature difference of the plume and ambient air, material burn rate, radius of the pile, and wind speed (Bjorklund, Bowers, & Dodd, 1998). Varying plume rise with time could improve ground concentration values of the models, especially if sampling points are extremely close to the source.

For this research, one-hour averaged weather data for one location was used as input. To improve the models, a more defined grid and shorter time span could be used to improve the dispersion models (Yerramilli et al., 2011), e.g., using 1 km gridded weather data with 0.5-hour resolution. Additionally, resources limited the ground sampling to only three stations. Future research should consider implementing a larger number of ground sampling stations, ideally laid out in an array to improve direct comparisons to the models.

Conclusion

Overall, the models did not perform well with one-hour weather averages as inputs. ALOHA, in general, did not accurately predict ground concentrations and predicted zero ground concentrations in most cases. HPAC also poorly predicted ground concentrations or, at best, predicted very low values. HYSPLIT performed the best out of the three models, predicting ground concentrations of CO_2 for two of the four open burn days. Using downloadable high resolution weather data, DW, marginally improved model performance.

For future studies, a more defined and robust sampling grid must be used to collect ground data. Weather changes frequently during a very short time frame and most dispersion models currently cannot account for these near-continuous variations. In addition, robust data should be collected to determine actual emission factors. Data like composition of the waste, weight and volume before and after the burns, and burn times with distinct identification of flaming and smoldering phases should be collected.

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III. Conclusions

Since the beginning of the wars in Iraq and Afghanistan, disposal of deployed military waste has been a challenge. The lack of off-base disposal options, and the inherent security concerns with hauling waste off the base, force the US military to find solutions within the fenceline. Technologies, such as incinerators and burn boxes, are used when available, but high waste generation rates require bases to resort to open burning. Sampling military personnel exposure to pollutants is labor and equipment intensive, leading to this research to investigate whether using software to model downwind pollutant concentrations is a suitable alternative. Various other studies have shown that ALOHA, HPAC, and HYSPLIT can predict downwind concentrations within acceptable parameters if the inputs into the system are well determined beforehand. Three main inputs in all the models are source strength, release height, and weather data. Any error in any of these inputs will produce error in concentration but the most important component is the weather data.

In Chapter 1, two research questions were posed and are listed below with brief responses:

Research Questions

1. *How well does air dispersion software predict downwind dispersion?*

As discussed in Chapter 2, the models did not perform well with one-hour weather averages as inputs. ALOHA performed poorly in predicting CO_2 concentrations, with many zero concentrations being noted. By design, ALOHA does not handle particulate matter. HPAC performed similarly or, at best, predicted extremely low CO_2 and $PM_{2.5}$ concentrations. Using 1 hour averaged surface weather data as input for HYSPLIT

produced similar results as ALOHA and HPAC. HYSPLIT either missed altogether or predicted extremely low concentration values. Using downloaded archived NAM weather data (DW) with 12 km and 1 hr resolution, HYSPLIT predicted CO_2 concentration for two of the four burn days. Overall, HYSPLIT did not predict $PM_{2.5}$ values for any of the days within the statistical test criteria. Refer to Appendix A for more information on various dispersion software and performance.

Overall, the models did not perform well with one-hour weather averages as inputs. ALOHA, in general, did not accurately predict ground concentrations and predicted zero ground concentrations, in most cases. HPAC also poorly predicted ground concentrations or, at best, predicted very low values. HYSPLIT performed the best of the three models, having predicted ground concentrations of CO_2 for two of the four open burn days. Using downloadable high resolution weather data, DW, marginally improved model performance.

Since the models did not detect ground concentration values using surface weather over a 3hr sampling time, an attempt has been made to standardize dispersion models to see if their contours looked similar using the same weather data. The models, HPAC, HYSPLIT, and ALOHA were ran using only one hour averaged weather input, wind and direction for the 30 Sep open burn. HYSPLIT and HPAC were imported into ArcGIS to display the results. Appendix D contains the results. Results show that ALOHA, HPAC, and HYSPLIT had similar plume direction, but contour size/dispersion differed as distance from the source increased.

2. *Which air dispersion software is most useful to Bioenvironmental Engineer in a deployed environment?*

The results of this study indicate that if the Air Force Bioenvironmental Engineer is considering the use of dispersion modeling in lieu of sole reliance on ground sampling, the preferred software solution is HYSPLIT with high resolution weather data. This assumes that the list of possible solutions is limited to ALOHA, HPAC, and HYSPLIT, according to the initial assumptions of the study (e.g., freely available, easy to use, appropriate for deployed use, etc.). Note, however, that emission factors for pollutants of concern are necessary and limited research has been conducted to establish such emission factors. Also, it is important to note that no consensus exists in the literature on which pollutant(s) is/are the cause of health problems described previously in this thesis. Until toxicological research better answers the root cause question, a recommended approach would be to document exposure estimates for the host of pollutants described in Chapters 1 and 2. Logically, doing this likely warrants continued reliance on ground-based sampling, but limited resources (i.e., people and sampling equipment) suggests consideration of using models to supplement air sampling. HYSPLIT handles both gaseous and particulate matter, which in theory allows it to model all the pollutants.

Strength and Limitations

The main strength of the research is prototyping the idea of using common dispersion models in lieu of ground-based sampling. To clarify, dispersion models are probably best used *in conjunction* with and not as a replacement for ground-based sampling. Conducting air sampling campaigns in theater for burn pit-related purpose is

both manpower and equipment intensive and this research brings attention to a possible solution.

There are numerous limitations to this research. One limitation is the need to determine emission factors based on estimated amount of carbon on the pile, which is affected by waste composition. Some literature exists and it is expected that a full suite of emission factors will be published, based on research performed at Tooele Army Depot, in conjunction with the work presented here. A second limitation is the identified need to factor in estimated burn rates and amount of carbon consumed over time. A third limitation is that the ground sampling stations were extremely close to the emission site. Future research should consider deploying an array of samplers at greater distances, in order to improve statistical comparisons between dispersion models and ground samples. The buoyant plume rise must be considered especially close to the source since it could be the dominant force behind concentration for a near location. In addition, there were not enough ground weather stations to capture variability in the wind direction. The fourth limitation related to the weather data used in the models. One hour averaged weather data, which is shown in Appendix C, is not sufficient to simulate dispersion during highly variable weather conditions and when modeling in the microscale (e.g., distance on the order of < 5 km vs. > 10 km, etc.).

Recommendations for Future Research

As described previously, a recommendation is to improve the weather used in modeling, such as more frequent surface weather updates. HYSPLIT can use downloaded weather data and user entered surface weather data independently or together. Currently, HYSPLIT user entered weather data is limited to only six time

points for a single location and multiple files cannot be created because HYSPLIT overwrites the previous file. Therefore, HYSPLIT code should be modified to accept as much user data as available for multiple locations, various elevation, and at a smaller time increments.

Related to the discussion above, another possible research topic would be to use local surface weather data combined with downloaded NAM weather data to see if the HYSPLIT model produces different results. For this research, HYSPLIT was set to use Gaussian horizontal and particle vertical dispersion, but HYSPLIT can perform dispersion by other calculation options, particle in vertical and horizontal, Top-Hat horizontal particle vertical or others. These calculation options could be explored as well.

Advantages of ALOHA are its ease of use, models can be run quickly, and minimal set-up time is required. However, ALOHA likely cannot be improved upon without extensively modifying the software. An alternative solution would be to perform multiple runs for each hour, then averaging the concentration values manually to see if there is an improvement in the comparison to the ground concentration values. But with few output options, ALOHA is more useful as a planning tool and for responding to a release, and perhaps less practical in predicting personnel exposures from such sources as burn pits.

A newer version of HPAC could be investigated because it has the capability to download similar gridded weather data to HYSPLIT. The output from that model should be compared to HYSPLIT to see which one is better in predicting ground concentrations. Other dispersion software should be looked at to see if there are better options available.

AERMOD is the EPA's choice for modeling dispersion and should be investigated in the future.

Future research should also consider using a more robust, larger array of ground sampling stations to improve the comparisons to dispersion models. These samplers should be positioned further apart, if possible. Finally, a more extensive library of emission factors is necessary, including factors based on different burn conditions (e.g., waste composition, amount of accelerant used, volume of waste burned, open burn vs. incinerator vs. burn box, etc.).

Appendix A: Expanded Literature Review

Background

Litigation issues have also surfaced as deployers are coming back from deployment have filed suit against the operators of those burn pits in Iraq and Afghanistan. The plaintiffs claim that the trash burned produced smoke that might have had some negative impacts on the military members deployed to various bases with open burning as the primary method of waste disposal. Contractors were not paying enough attention to the materials burned until Joshua Eller and 200 others, deployed to Iraq, filed suit in 2008 against KBR for their improper burn pit operations. Deployed personnel saw batteries, plastics, asbestos, chemical and medical waste, human remains, and many other prohibited waste burned in Iraq (Kurera, 2011). Therefore, burning various wastes can produce toxins that are harmful to the environment and personnel. The long-term effects of open burning can have dire consequences and health effects due to exposure to burned pit smoke and may not surface for a numerous years after a member actually returns from a deployment. Mission readiness is extremely important in a deployed environment where soldiers must remain alert at all times, thus exploratory studies should be conducted to see if the emission levels from burn pits exceed known standards for a deployed environment.

One great concern with sampling and gathering reliable data in the CENTCOM area of operations is the weather. Frequent dust storms can skew the data significantly and make the use of model under-predict ground concentration. For severe dust storms, PM_{10} can exceed 1000 $\mu g/m^3$ (Draxler, Gillette, Kirkpatrick, & Heller, 2001). The three levels of dust storms are severe dust storms (SD), moderate dust storms (MD) and local

dust events (LDE). SD = days when visibility is reduced to <200 m; MD = visibility is <1,000 m and LDE when total suspended particulate matter >150 μg/m^3/hr (Yang, Squires, & Lu, 2001). Dust storms are frequent in Afghanistan and Iraq and can occur anywhere from 10% to 50% of days during the summer months (Goudie & Middlwton, 2000). Since dust storms are so frequent in Iraq and Afghanistan it is difficult to tell if burn pits contribute a large amount to the ambient levels.

Open Burning Emissions

Open burning is defined by Lemieux as the "unenclosed combustion of materials in an ambient environment which can include unintentional fires such as forest fires, prescribed burns to get rid of excessive vegetation, arson, or fireworks" (Lemieux, Lutes, & Santoianni, 2004). Open burning of solid waste has been a long practiced procedure. It is an easier alternative of reducing the amount of waste landfilled in developing countries and deployed environments. Since the start of the operations in Afghanistan in 2001 and Iraq war in 2003, the Department of Defense (DOD) has had difficulty in finding a solution in managing the reduction of solid waste safely. Therefore, using open burn pits, as well as in landfills and incinerators are typical disposal methods. Open burning is normally performed on earth surface or in a shallow excavated area (Trimble, 2010). In addition to open burning, there are many waste incineration techniques with some of them being, air curtain incineration, moving or fixed grate incineration, rotary kiln, and others. All incineration methods produce some emissions thus should be monitored. The purpose of incineration is to reduce the volume of waste that has to be disposed of in a landfill and can reduce the volume of waste by 90% or more.

Numerous parameters influence emission levels for open burning. If open burning occurs at low combustion temperatures due to poor mixing of fuel and air, emission levels can be 2000 times higher than those from stacks of modern municipal waste combustors. Various other factors can influence emission levels like composition of waste. Combustion parameters like the fuel to air ratio, the compaction of the waste, the moisture content, which all could impact combustion temperature and induce smoldering (Gullett et al., 2009). Open burning can produce a host of pollutants some of which are carbon monoxide (CO), methane (CH_4) and other light hydrocarbons, volatile organic compounds (VOCs) such as benzene, and semi-volatile organic compounds (SVOCs) including polycyclic aromatic hydrocarbons (PAHs) such as benzo-a-pyrene , and particulate matter. Depending on waste composition, varying amounts of metals such as lead (Pb) or mercury (Hg) may be emitted. Polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDDs/Fs) or polychlorinated biphenyls (PCBs) which are known carcinogens can be emitted as well (Lemieux et al., 2004).

Based on the burn temperature and waste composition, mass percentages burned was found to be 90% during the flaming phase plus 10% during the smoldering phase (de Zarate O.I., Ezcurra, Lacaux, & Van Dinh, 2000). Therefore, most of the toxicants produced during open burning may be the result of low-temperature burning of a small fraction of the initial mass burned. Smoldering produces most of the CO, CH_4, Non-Methane Organic Compound (NMOC), and primary organic aerosol. Smoldering and flaming frequently occur simultaneously during a fire and the phases maybe indistinguishable by a naked eye. Flaming normally occurs in the 1400 K range and glowing or smoldering occurs 800–1000 K range (Akagi et al., 2010). There are multiple

reasons why smoldering is prevalent in open source burning. After the quick flaming phase, which destroys the majority of the combustible material, smoldering dominates and persists due to lack of fuel, poor air circulation in the remaining material, and wet waste.

Many studies have been performed on open burning in recent years to quantify emission levels being emitted from the burns. Municipal solid waste, biomass, and other wastes have been analyzed to determine emission levels. Biomass burning (BB) emits non-methane organic compounds (NMOC), O_3, PM and other organic compounds. BB has shown that it contributes four times more NMOC previous research studies (Akagi et al., 2010). Ozone at ground level can be harmful to people, animals and plant life therefore it needs to be monitored and controlled.

Other type of waste has been examined extensively is municipal solid waste burning (MSW). Since domestic waste can be made up of hazardous household wastes like plastics, paints, solvents, electronic wastes, organic wastes, and discarded tires, emissions open burns is believed to be a significant source of (PCDDs/Fs) (Gullett et al., 2009). This waste mixture could be very similar to what is produced in the deployed environment thus limiting the type of the materials being burned could be beneficial in reducing concentrations of toxic emissions. This study has shown that PCDD/F emission factors were five times higher than in other comparable research studies with domestic waste. The waste that was burned in barrels had levels 2000 times higher than from typical municipal waste incinerators. These emission factor levels are more typical for a smoldering phase than a flaming phase (Gullett et al., 2009). Unmonitored open burns normally tend to smolder after a short flaming phase. In a deployed environment where

solid waste disposal practices are not the main concern this is more likely to occur. This shows that it is critical to control the burning technique and avoid smoldering phase of open burning if possible.

Another study showed that the formation PCDD/F could be attributed to adding MSW waste to a coal burning operation. The study conducted was performed by burning coal to see what was contributing to the formation of PCDD/F. It showed that burning coal alone produced low concentrations of PCDD/F, approximately 400 ng/m^3, compared to 3000 ng/m^3 when solid waste was added (Gullett B. & Raghunathan, 1997). Thus, organic compounds contribute to the formation of dioxin like compounds. It is also important to note that PCDD/F formation occurs at low combustion temperatures, 200 to 400 ^oC ranges, therefore if ACIs are used proper controls must be established to make sure that the temperatures are maintained above the formation range of dioxins.

Research of burning waste in 55 gallon drums method, which is typical for waste incineration techniques used in rural areas, showed the formation of PCDD/F as well. Varied waste composition mixtures were used to conduct this research. Some items burned were paper, plastics, food, textiles, wood, and metals. The research showed that not just the burn temperature is important but that composition of the waste plays a key role in the formation of dioxin like compounds (Gullett, Lemieux, Lutes, Winterrowd, & Winters, 2001).

Another biomass was that was analyzed during open burning was cereal waste. Cereal waste was burned in Spain to determine the difference between the flaming and smoldering phases of the burn and to find how much carbon is being converted to CO_2. Experiments showed that during the faming phase 88% of carbon is converted to CO_2 and

only 3% to CO. During smoldering, the percentage of CO_2 produced was reduced to 74% and CO released increased to 17%. Also, the flaming phase destroyed 90% while the smoldering phase only destroyed 10% of the combustible waste (de Zarate O.I., Ezcurra, Lacaux, & Van Dinh, 2000). While this may be typical for biomass waste further study is needed to find out if the destruction percentages are similar for MSW and other wastes that are more common in theater of operations. This factor is important to consider since smoldering can have a greater release of other pollutants as well. A follow on study also determined that per 1 kilogram of cereal waste burned approximately 410 grams of carbon 3.3 grams of nitrogen is produced (de Zárate O.I., Ezcurra, Lacaux, Van Dinh, & de Argandoña, 2005).

A burning of plastics in an open pit was investigated as well. It was found that carcinogenic polycyclic aromatic hydrocarbons (PAHs) and nitropolycyclic aromatic hydrocarbons (nitro-PAHs) have been identified in airborne particulate organic matter extracts. Various plastics like Polyvinyl chloride (PVC) Polyethylene terephthalate (PET), polystyrene (PS), and polyethylene (PE) were burned in this research and it was found that PVC was most mutagenic, followed by PET, and PS (Lee, Wang, & Shih, 1995). PAHs are well-known mutagenic or carcinogenic compounds, which are generated from incomplete combustion or during the smoldering phase burn of urban or municipal solid waste containing various amounts of paper, rubber, PE, PVC, and other materials (Nishioka, Chang, & Lee, 1986).

Estimating Carbon Content

Table 8: Carbon Content in Waste (Pipatti et al., 2006)

MSW component	Dry matter content in % of wet weight [1]	DOC content in % of wet waste		DOC content in % of dry waste		Total carbon content in % of dry weight		Fossil carbon fraction in % of total carbon	
	Default	Default	Range	Default	Range [2]	Default	Range	Default	Range
Paper/cardboard	90	40	36 - 45	44	40 - 50	46	42 - 50	1	0 - 5
Textiles [3]	80	24	20 - 40	30	25 - 50	50	25 - 50	20	0 - 50
Food waste	40	15	8 - 20	38	20 - 50	38	20 - 50	-	-
Wood	85 [4]	43	39 - 46	50	46 - 54	50	46 - 54	-	-
Garden and Park waste	40	20	18 - 22	49	45 - 55	49	45 - 55	0	0
Nappies	40	24	18 - 32	60	44 - 80	70	54 - 90	10	10
Rubber and Leather	84	(39) [5]	(39) [5]	(47) [5]	(47) [5]	67	67	20	20
Plastics	100	-	-	-	-	75	67 - 85	100	95 - 100
Metal [6]	100	-	-	-	-	NA	NA	NA	NA
Glass [6]	100	-	-	-	-	NA	NA	NA	NA
Other, inert waste	90	-	-	-	-	3	0 - 5	100	50 - 100

[1] The moisture content given here applies to the specific waste types before they enter the collection and treatment. In samples taken from collected waste or from e.g., SWDS the moisture content of each waste type will vary by moisture of co-existing waste and weather during handling.

[2] The range refers to the minimum and maximum data reported by Dehoust *et al*., 2002; Gangdonggu, 1997; Guendehou, 2004; JESC, 2001; Jager and Blok, 1993; Würdinger *et al*., 1997; and Zeschmar-Lahl, 2002.

[3] 40 percent of textile are assumed to be synthetic (default). Expert judgement by the authors.

[4] This value is for wood products at the end of life. Typical dry matter content of wood at the time of harvest (that is for garden and park waste) is 40 percent. Expert judgement by the authors.

[5] Natural rubbers would likely not degrade under anaerobic condition at SWDS (Tsuchii et al., 1985; Rose and Steinbüchel, 2005).

[6] Metal and glass contain some carbon of fossil origin. Combustion of significant amounts of glass or metal is not common.

To estimate how much carbon content there is in waste, the waste composition must be determined beforehand. Using the table above, the weight of the pile or it can be estimated based on volume and density, and known waste composition amount of combustible carbon can be determined. After carbon weight has been determined, CO_2 emission rate can be calculated by using equation 5.2 from IPCC guide.

$$CO_2 = MSW * \sum_J (WF_j * dm_j * CF_j * FCF_j * OF_j) * 44/12 \qquad (1)$$

Where CO_2 emissions is in mass per time, MSW is the total waste burned per time, WF is a fraction of a waste type/material component j in MSW, dm is dry matter content in waste component j, CF is a carbon fraction in dry matter component, FCF is the fossil

carbon component, OF being the oxidation factor for the entire waste, and 44/12 is a conversion factor of C to CO_2.

Additional Dispersion Modeling Review

The basic Gaussian dispersion equation is used to approximate downwind pollutant concentration is as follows:

$$c(x,y,z,t) = \frac{Q}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} exp\left[-\frac{1}{2}\left[\left(\frac{x-ut}{\sigma_x}\right)^2 + \left(\frac{y}{\sigma_y}\right)^2 + \left(\frac{z}{\sigma_z}\right)^2\right]\right] \quad (2)$$

Where Q is total amount of material released at one instance in time, the $\sigma_x, \sigma_y,$ and σ_z determine how the plume will disperse in the atmosphere, x, y, and z are the coordinates from the source, and u in the average wind speed in a horizontal plane. Over the years many other dispersion equations have been developed for various sources like open or stack emissions, dispersion equations that account for atmospheric or an inversion layers, released at elevated sources and for various atmospheric stability conditions.

Additional Plume Rise Information

Equation 4 is used under stable atmospheric conditions, if the conditions are not stable other equations 4-6 must be used. When potential temperature change is less than or equal to zero ($\partial\theta/\partial z \leq 0$) equations bellow should be used per OBODM users guide volume II.

$$\Delta h_{cs}(x) = \begin{Bmatrix} \left[\frac{3\,F}{u\gamma_c^2\,S}\left[1 - cos\left(S^{1/2}\,\frac{x}{u}\right)\right] + \left(\frac{r_R}{\gamma_c}\right)^3\right]^{\frac{1}{3}} - \left(\frac{r_R}{\gamma_c}\right); x \leq \pi u S^{-\frac{1}{2}} \\ \left[\frac{6\,F}{u\gamma_c^2\,S} + \left(\frac{r_R}{\gamma_c}\right)^3\right]^{\frac{1}{3}} - \left(\frac{r_R}{\gamma_c}\right); x > \pi u S^{-\frac{1}{2}} \end{Bmatrix} \quad (3)$$

$$\Delta h_{cn}(x) = \left[\left(\frac{3\,Fx'^2}{2\gamma_c^2 u^3} + \left(\frac{r_R}{\gamma_c}\right)^3\right)^{\frac{1}{3}}\right] - \left(\frac{r_R}{\gamma_c}\right) \quad (4)$$

$$x' = \begin{pmatrix} x & ; x \leq 3.5x^* \\ 3.5x^* & ; x > 3.5x^* \end{pmatrix} \quad (5)$$

$$x^* = \begin{pmatrix} 14F^{\frac{5}{8}} & ; F \leq m^4\,s^{-3} \\ 34F^{\frac{5}{8}} & ; F > 55m^4 s^{-3} \end{pmatrix} \quad (6)$$

Additional Atmospheric Stability Lit Review

Atmospheric stability is the ability of the atmosphere to resist vertical motion. Therefore, if a parcel of air is forcefully moved to a higher elevation and atmosphere is stable that parcel of air will have the tendency to return to its original position, but if the atmosphere is unstable, that parcel of air will continue moving to a higher elevation until it reaches equilibrium with the local environment (Wallace & Hobbs, 2006). Pasquill-Gifford came up six stability classes, which are depended on net ground radiation, which depends on what day of year it is, latitude and time of day, wind speed, and cloud cover. The six stability classes are A) extremely unstable, B) moderately unstable, C) slightly unstable, D) neutral, E) slightly stable, and E) moderately stable.

Table 9: Pasquill-Gifford Stability Categories (Schnelle & Dey, 2000)

Surface Wind (Measured at 10 m)		Day-Time Insolation			Night-Time Cloudiness	
(m/sec)	(mph)	Strong	Moderate	Slight	Thinly Overcast or ≥ 4/8 Cloudiness*	≤ 3/8 Cloudiness*
<2	4.5	A	A-B	B	–	–
2-3	4.5-6.7	A-B	B	C	E	F
3-5	6.7-11.2	B	B-C	C	D	E
5-6	11.2-13.4	C	C-D	D	D	D
>6	13.4	C	D	D	D	D

* The *degree of cloudiness* is defined as that fraction of sky above the local apparent horizon that is covered by clouds.

Notes:

1. *Insolation* is the rate of radiation from the sun received per unit of earth's surface.
2. Strong insolation corresponds to sunny mid-day in summer. Slight insolation corresponds to similar conditions in mid-winter.
3. For A-B, B-C, etc. take the average of A and B values.
4. Night refers to the period from 1 hour before sunset to 1 hour after dawn.
5. Regardless of wind speed, the neutral category D should be assumed for overcast conditions during day or night and for any sky conditions during the hour preceding or following night.

1 mph = 0.4470 m/sec
1 m/sec = 2.237 mph

A - extremely unstable
B - moderately unstable
C - slightly unstable
D - neutral
E - slightly stable
F - moderately stable

The stability criteria will affect pollutant dispersion downwind of the source. Depending on the stability the plume will behave differently, therefore different equations must be used to calculate the downwind ground concentration. The five basic plume types are looping, conning, fanning, fumigating, and lofting.

Looping plume forms when atmosphere is unstable and there is a high degree of turbulence. These plume types typically form in hot clear days with low to moderate wind velocities. Pollutant ground concentrations can be high but due to high turbulence do not persist for a long time.

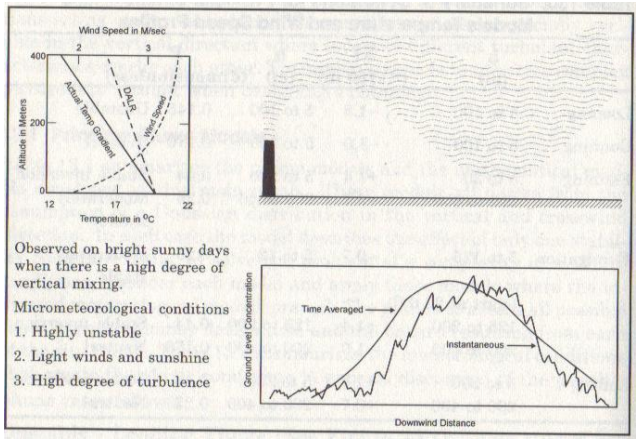


Figure 8: Looping Plume (Schnelle & Dey, 2000)

Coning plumes form under neutral to slightly unstable atmospheric conditions. Light winds and cloud cover are likely during neutral conditions. Ground concentrations

can be quite high and can persist for an extended period. Gaussian dispersion models are most representative of these types of plumes.

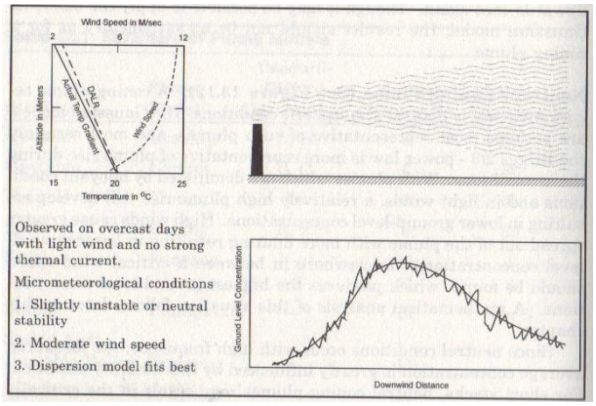


Figure 9: Coning Plume (Schnelle & Dey, 2000)

Fanning plume forms under stable conditions during morning hours when early inversion persists. This plume disperses horizontally and not vertically therefore ground concentrations are very low. If high level inversion persists and low level inversion breaks up the layer below becomes unstable where good mixing can occur, fumigation plume forms where pollutant ground concentrations can be very high.

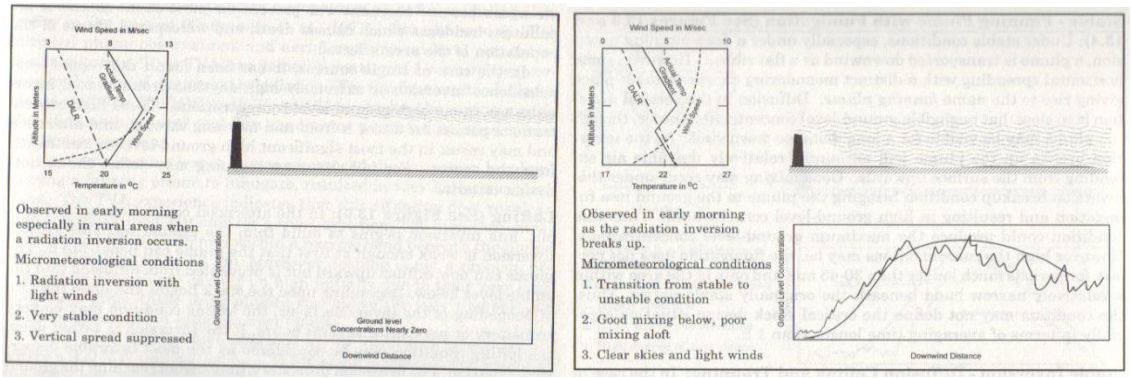


Figure 10: Fanning Plume (left), Fumigating Plume (right) (Schnelle & Dey, 2000)

Last type of plume is the lofting plume. Ground inversion forms creating a stable layer which prevents mixing during late afternoon. Above the stable layer there is an

unstable layer which allows mixing of pollutants. This is normally the best time for pollutant release due to low ground concentrations.

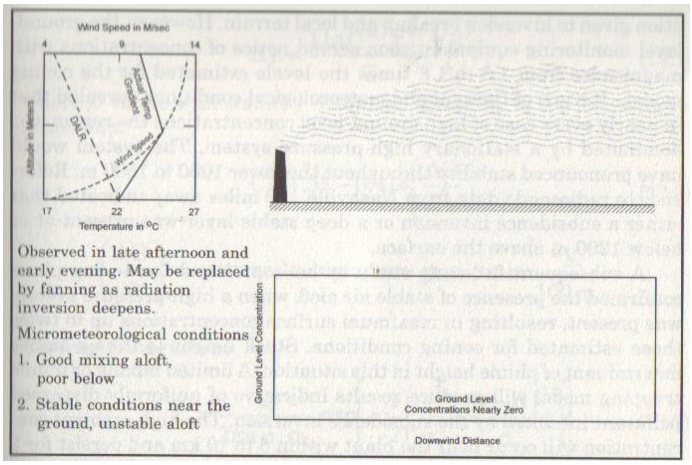


Figure 11: Lofting Plume (Schnelle & Dey, 2000)

Additional ALOHA Information

In one study ALOHA was compared to five other dense gas dispersion modeling software. The models were used to predict source emission and downwind ground concentrations of chlorine gases, which were released in three different accident locations, Fetus Missouri, Macdona Texas, and Granitville SC. Most models predicted values were not greater than a factor of two from each other. This study concluded that estimating source release term is the most important factor in determining downwind concentration (S. Hanna et al., 2008). Without reliable pollutant source data, dispersion models become less useful.

ALOHA was also compared to Hazard Prediction Capability (HPAC) program, which uses Second Order Closure Integrated Puff (SCIPUFF) model and Emergency Prediction Information Code (EPIcode) during low wind conditions and a range of up to 100 meters. EPIcode and ALOHA are primarily used by federal agencies for emergency planning while HPAC is used by Department of Defense (DOD). The experiment has

shown that Gaussian dispersion models tend to over predict concentrations during low wind conditions (Sawyer, 2007).

Additional HYPLIT and AERMOD Information

One study was conducted to compare the four different dispersion modeling software two of which were AERMOD and HYSPLIT. Pollutant was released from a stack and concentration was modeled by software. AERMOD and HYSPLIT maximum concentration were similar but occurred at different locations based on how each model uses meteorological input and how each model disperses the pollutant (Caputo, Giménez, & Schlamp, 2003). The dispersion modeling software calculates atmospheric stability differently therefore, concentrations results are different as well.

In study performed by EPA of dioxin release from oil burning from the BP spill in the Gulf of Mexico EPA used AERMOD and HYSPLIT to model short and long range dispersion and deposition. AERMOD results showed that with higher wind speeds ground concentrations were also higher close to the source due to wind keeping the plume close to the ground. The concentrations were reported 50 meters to 2500 meters downwind from the source. HYSPLIT dispersion model produced results for a 10 by 10 degree grid. The maximum concentrations were 50 km south of the spill site and that approximately 40% of the pollutant was deposited in the 10 by 10 grid (Schaum et al., 2010).

In the late 90's EPA and American Meteorological Society developed AERMOD regulatory dispersion modeling software. AERMOD is a steady-state Gaussian dispersion model that uses weather data, terrain data, and surface characteristics to model dispersion from a source (Cimorelli et al., 2010). AERMOD is EPAs preferred method

of modeling dispersion. It is intended to be used to model dispersion from industrial sources and in short range of up to 50km (Perry et al., 2005).

There are two primary preprocessors to AERMOD, AERMET, which processes weather data, and AERMAP, which processes terrain data. Preprocessor AERMET performs quality checks on the weather data, merges upper air and surface weather data, and produces output files for use in AERMOD. AERMAP uses local Digital Elevation Model (DEM) file, which can be downloaded from USGS site, and creates a terrain file to be used in AERMOD as well.

Numerous test have been conducted to see how well AERMOD modes downwind dispersion. One study compared AERMOD to Advanced Dispersion Modeling System (ADMS) and Industrial Source Complex Model Version 3 (ISC3) where buoyant and non-buoyant tracers were used from open and stack sources. ADMS and AERMOD under predicted ground concentrations by a factor of two while ISC3 over predict the observed values by a factor of two (S. R. Hanna et al., 2001). Another study compared AERMOD to ISCST3, Hybrid Plume Dispersion Model (HPDM) the Rough Terrain Diffusion Model (RTDM) and the Complex Terrain Dispersion Model Plus Algorithms for Unstable Situations (CTDMPLUS). Non-buoyant flat terrain sources, elevated buoyant sources with flat terrain, open and stack sources, and complex terrain sources were examined. AERMOD performed well under flat terrain buoyant and non-buoyant releases when ISCST3 over predicted and CTMDPLUS under predicted the observation concentration values. In long-term studies for buoyant stack releases in flat, complex, and hilly terrain, AERMOD performs well with the best Q-Q plot for flat terrain, performs well in hilly terrain and complex terrain conditions. ISCST3 under predicted in

flat terrain, performed well under hilly terrain and over predicted concentration values by a factor of 10 in complex terrain. HPMD performed exceptionally well in flat terrain, over predicted in hilly terrain, and performed very well in complex terrain conditions (Perry et al., 2005).

Appendix B: Dispersion Model Comparison

Table 10: Dispersion Model Comparison

Dispersion Software	Dispersion Type	Models	Weather	Terrain	Input	Output	Learning Curve	AOR usability
ALOHA (EPA, V 5.4.1.2)	Gaussian	Gas	One point wind, temperature, humidity	No	Simple	Graphical and text	Low	High
AERMOD (EPA, V 11103)	Gaussian	Gas and particle	Upper morning air, surface wind, local winds over time	Yes	Complex	Text	Very High	Low
HYSPLIT (NOAA, V 4.9)	Gaussian puff and/or particle	Gas and particle	Four-dimensional downloaded weather (wind, temp, humidity)	Weather following terrain	Moderate	Graphical and text	Moderate	Medium
HPAC (DTRA, V 4.04)	Gaussian puff	Gas and particle	Four-dimensional weather (downloaded or user input)	Yes	Moderate	Graphical and text	Moderate	Medium

Software

ALOHA, AERMOD, and HYSPLIT software can be downloaded from the web for free. ALOHA and AERMOD are located on EPA website, http://www.epa.gov/osweroe1/content/cameo/aloha.htm and http://www.epa.gov/ttn/scram/dispersion_prefrec.htm respectively. HYSPLIT can be found on the NOAA site, http://ready.arl.noaa.gov/HYSPLIT.php. The user can run the dispersion model from the site and the user would not have to register to download the software and install it on a personal computer but the web software does not have as many features as the downloaded software. HPAC is software developed by DTRA

which only available following an application and approval process. Instructions for the application for obtaining the software can be found in HPAC user's guide that can be found on the web.

ALOHA (description, dispersion type, source input, weather input)

Each software has slightly different applications therefore, their input requirements are different as well. ALOHA is a computer program primarily intended for use by people or agencies who are responding to chemical releases. The software can only model gas dispersion from a continuous or instantaneous source. It uses a Gaussian dispersion model which based on statistical parameters disperse pollutant based on wind velocity and distance from the source. The basic inputs are the site location where a user can select a city from a drop down list or the user can input coordinates in a form of latitude and longitude. Then the user would select a gas that he or she would want to model from the list. Some of the gases that can be modeled are CO, CO_2, SO_2, Cl_2 and many others. The weather inputs are straight forward for ALOHA software. The user inputs wind speed in knots, m/s, or mph and direction of the wind at a certain height. The user can also set cloud cover from complete to none, which will determine stability class conditions. The user also enters temperature in either Fahrenheit or Celsius since gas phase is temperature depended. The last condition for weather is to select amount of humidity from rain to arid.

ALOHA (terrain, source)

ALOHA assumes the terrain is flat in every scenario. The user can specify surface roughness either open country, urban or forest, or open water. If the user knows the actual value, he or she can enter that as well. After setting up atmospheric parameters the

user needs to enter the source data. There are four options for a source, which are direct, puddle, tank or gas pipeline. If selecting direct source the user needs to specify if the emission is continuous or instantaneous and amount released into the atmosphere whether in grams or kilograms, liters or gallons, pounds cubic feet or meters.

ALOHA (output)

ALOHA generates two basic outputs, a graphic and a text output. If the user has MARPLOT installed the output can be displayed on a map. Either the user can specify parts per million (ppm), milligrams/m^3, milligrams/liter, or grams/m^3 for ground concentrations. The text output is very basic and has only concentration downwind along a centerline from the source.

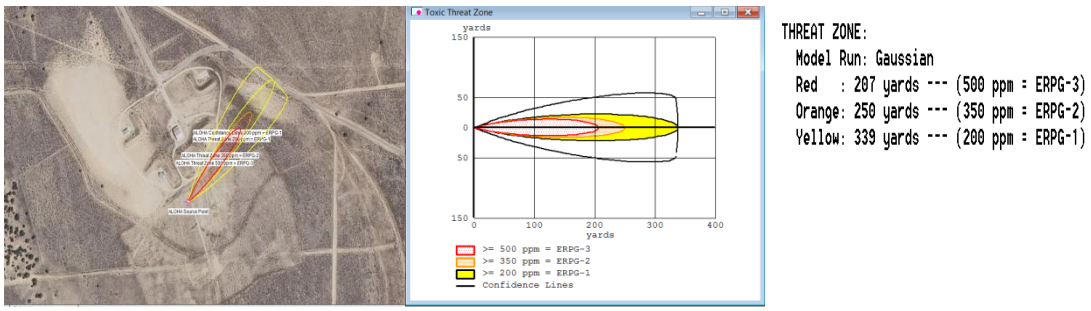


Figure 12: Example output from ALOHA (graphical and text)

AERMOD (description, dispersion type, source input, weather input)

In the late 90's EPA and American Meteorological Society developed AERMOD regulatory dispersion modeling software. AERMOD is a steady-state Gaussian dispersion model that uses weather data, terrain data, and surface characteristics to model dispersion from a source. AERMOD is EPAs preferred method of modeling dispersion. It is intended to be used to model dispersion from industrial sources and in short range of up to 50km. AERMOD is an executable file that reads various user prepared text files to model pollutant dispersion. AERMOD comes with AERMET, and AERMAP pre-

processors or executable files. AERMET prepares text weather files (upper air weather or radiosonde data, hourly surface wind, and wind at source location if available) and merges the files to be used by AERMOD. AERMET also has its own preprocessors AERMINUTE and AERSURFACE. The hourly surface weather data that is processed by AERMOD refers to wind speeds from zero to three knots as calm, therefore some hours will have blank data fields when processed by AERMET. AERMINUTE uses two minute averaged winds which can be downloaded from National Climatic Data Center (NCDC) website and fills in the data gaps for AERMET. AERSURFACE is used to compute the surface characteristics in the local area. It computes surface roughness (z_o), albedo (r), and Bowmen ratio (B_o). To compute these factors the user must download land cover data in binary or tiff format from http://landcover.usgs.gov/natllandcover.php and use AERSURFACE executable to compute those factors. The output file generated is used by AERMET. After AERSURFACE and AERMINUTE are used to generate their respective output files AERMET is used to create weather files to be used by AERMOD for dispersion calculations. AERMET has a three-stage process where the first stage performs quality checks on the weather data, the second stage merges upper air, surface and onsite weather data, and third stage creates output files to be used by AERMOD.

AERMOD (terrain, source)

Terrain is computed by using another executable AERMAP. AERMAP uses either downloaded Digital Elevation Model (DEM) data or National Elevation Dataset (NED) files to compute surface elevation. It is recommended that NED data is used because DEM data has potential issues of inconsistent datums and could produce errors if

incorrect datum is selected. The files can be downloaded from http://seamless.usgs.gov/index.php in a CONUS area. The files must be in a GeoTIFF format or AERMAP will not be able to read the files. For more information, refer to AERMAP user's guide. After all the weather and the surface files have been generated by AERMET and AERMAP AERMOD is used to calculate concentration. The user must create a source input file where the user must define receptor locations in either Polar or Cartesian coordinate system. The user must also define source location (give x and y coordinates), source type (point, area, volume, etc.), and amount emitted in a period in a different text files to complete the input files for the AERMOD executable.

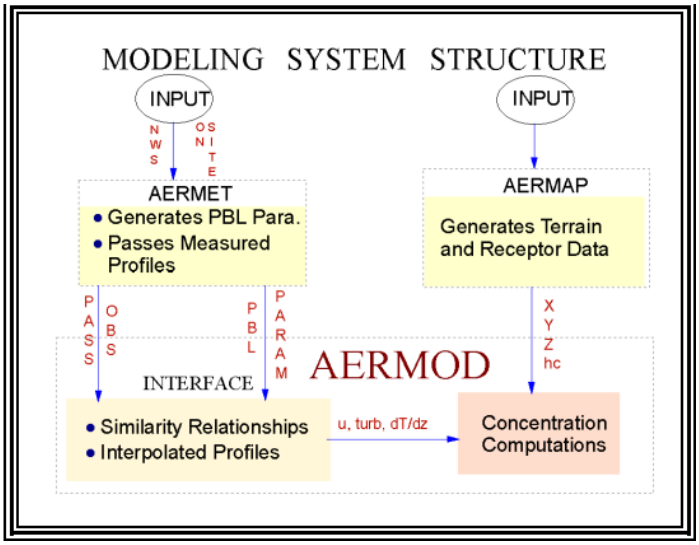
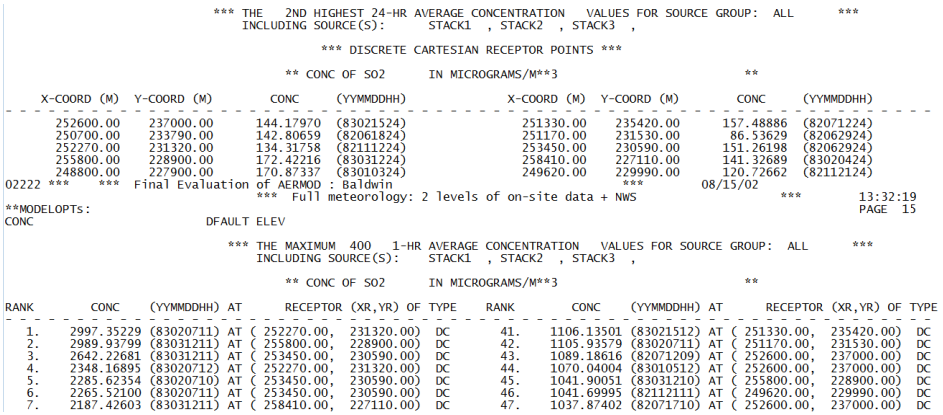


Figure 13: AERMOD Data Flow

AERMOD (output)

After AERMOD executable is ran, it creates an output text file with concentrations at predefined receptor locations and predefined averaging times. There is no graphic output therefore other drafting software must be used to create concentration contours if desired. The output is in $\mu g/m^3$ due to the input being in $g/(s\text{-}m^2)$ for open burning and if other output is needed it must be converted later.



```
                    *** THE   2ND HIGHEST 24-HR AVERAGE CONCENTRATION   VALUES FOR SOURCE GROUP:  ALL      ***
                        INCLUDING SOURCE(S):      STACK1  , STACK2  , STACK3  ,

                                  *** DISCRETE CARTESIAN RECEPTOR POINTS ***

                                ** CONC OF SO2      IN MICROGRAMS/M**3                      **

     X-COORD (M)  Y-COORD (M)        CONC     (YYMMDDHH)             X-COORD (M)  Y-COORD (M)        CONC     (YYMMDDHH)
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
       252600.00    237000.00      144.17970  (83021524)              251330.00    235420.00      157.48886  (82071224)
       250700.00    233790.00      142.80659  (82061824)              251170.00    231530.00       86.53629  (82062924)
       252270.00    231320.00      134.31758  (82111224)              253450.00    230590.00      151.26198  (82062924)
       255800.00    228900.00      172.42216  (83031224)              258410.00    227110.00      141.32689  (83020424)
       248800.00    227900.00      170.87337  (83010324)              249620.00    229990.00      120.72662  (82112124)
02222 ***    ***  Final Evaluation of AERMOD : Baldwin                    ***        08/15/02
                                ***  Full meteorology: 2 levels of on-site data + NWS                  ***        13:32:19
**MODELOPTs:                                                                                                    PAGE  15
CONC                      DFAULT ELEV

                           *** THE MAXIMUM  400   1-HR AVERAGE CONCENTRATION   VALUES FOR SOURCE GROUP:  ALL      ***
                               INCLUDING SOURCE(S):    STACK1  , STACK2  , STACK3  ,

                                    ** CONC OF SO2      IN MICROGRAMS/M**3                      **

RANK       CONC     (YYMMDDHH) AT      RECEPTOR (XR,YR) OF TYPE    RANK       CONC     (YYMMDDHH) AT      RECEPTOR (XR,YR) OF TYPE
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   1.    2997.35229 (83020711) AT ( 252270.00,  231320.00)  DC       41.    1106.13501 (83021512) AT ( 251330.00,  235420.00)  DC
   2.    2989.93799 (83031211) AT ( 255800.00,  228900.00)  DC       42.    1105.93579 (83020711) AT ( 251170.00,  231530.00)  DC
   3.    2642.22681 (83031211) AT ( 253450.00,  230590.00)  DC       43.    1089.18616 (82071209) AT ( 252600.00,  237000.00)  DC
   4.    2348.16895 (83020712) AT ( 252270.00,  231320.00)  DC       44.    1070.04004 (83010512) AT ( 252600.00,  237000.00)  DC
   5.    2285.62354 (83020710) AT ( 253450.00,  230590.00)  DC       45.    1041.90051 (83031210) AT ( 255800.00,  228900.00)  DC
   6.    2265.52100 (83020711) AT ( 253450.00,  230590.00)  DC       46.    1041.69995 (82112111) AT ( 249620.00,  229990.00)  DC
   7.    2187.42603 (83031211) AT ( 258410.00,  227110.00)  DC       47.    1037.87402 (82071710) AT ( 252600.00,  237000.00)  DC
```

Figure 14: Example Output from AERMOD (text)

The example output shows 2nd highest concentration values for a 24hr averaging period of SO_2 at specified receptors and max concentrations for one hour averaging time for different days and at specific distance away from the source.

HYSPLIT (description, dispersion type, source input, weather input)

HYPLIT is another software developed by NOAA and designed for regulatory agencies that perform diagnostic case studies, climatological analysis, and pollutant release emergencies. It uses Gaussian puff, particle dispersion, or a combination both to model downwind concentrations of a particular pollutant. The software can model particle or gas dispersion. It is a hybrid model, which uses Lagrangian and Eulerian methods. Langrangian model computes particle or puff dispersion by following the particle or puff. Eulerian method uses a reference point and computes concentrations as the puff passes its location. HYSPLIT has a graphic user interface (GUI), which helps the user with inputs to generate a dispersion model. The inputs are similar to ALOHA where the user enters the location of the source, the date of the release, and the type of the pollutant released. The weather data is downloaded from Air Resource Laboratory (ARL) by using the GUI that comes with HYSPLIT dispersion software. Weather comes

in various formats, forecast, appended, archived and reanalysis, which contain GFS (global low resolution), NAM (North American high-resolution) data with wind speeds, temperature, humidity, at various elevations and various times. The resolution of the data is anywhere from 2.5 degree resolution for global data to 12km resolution for the North American data and timescale is from 12hrs to 1hr for each data point.

HYSPLIT (terrain, source)

HYSPLIT uses internal terrain following sigma coordinated from the downloaded weather files to interpret elevation changes in the terrain. Sigma coordinate is a ratio of pressure at a certain point above the surface divided by the pressure at the surface. Unlike HPAC or AERMOD, which use DEM files to interpret terrain, HYSPLIT uses downloaded weather files. After location has been selected and weather files added the user needs to input pollutant source data. The user can select from particulate or gas dispersion and can add wet or dry removal based on weather conditions. The user needs to input emission rate in units per hour, hours of emission and release start time.

HYSPLIT (Output)

HYSPLIT can create two different concentration and deposition dispersion outputs based on user's preference. The software can generate a text output based on a specified grid or it can produce a graphical output. The concentration units will be the same as the input units. The user can change what and how information will be displayed in an output. The user can display concentration layers as averaged data or over time, how many concentration elevation layers to display, and specify important values to display in units/m^3. Also HYPSLIT can create an output to be displayed in Google earth and can create ArcGIS contours.

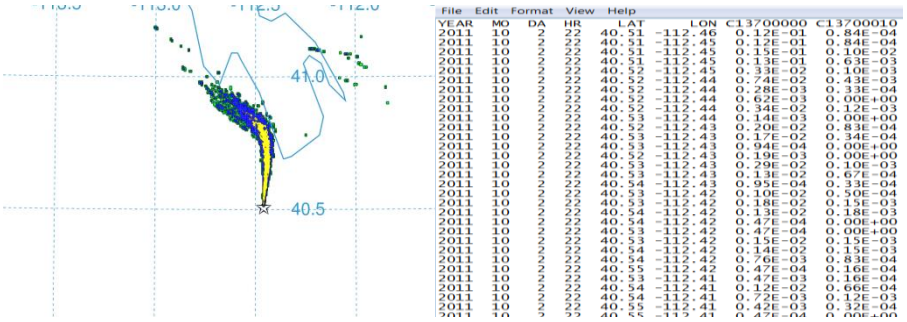


Figure 15: Example output from HYSPLIT (graphical and text)

HPAC (description, dispersion type, source input, weather input)

Defense Treat Reduction Agency (DTRA) developed HPAC modeling software. The software's primary is to model hazardous nuclear, biological and chemical releases and to predict fatalities from exposure to those releases. HPAC can model gas, particle, aerosol, or liquid release. HPAC uses SCIPUFF as atmospheric transport model. SCIPUFF is an advanced Lagrangian, Gaussian puff model that uses second-order turbulence closure scheme to model dispersion. User can enter his or her own local weather data or can download the data from DTRA server. Since HPAC has, an internal weather entering option. The user can download various data of the web, like the upper air data, and surface weather data or weather data at the source of emission and enter it to make better dispersion approximations. HPAC has greater flexibility than other software mentioned for entering weather data.

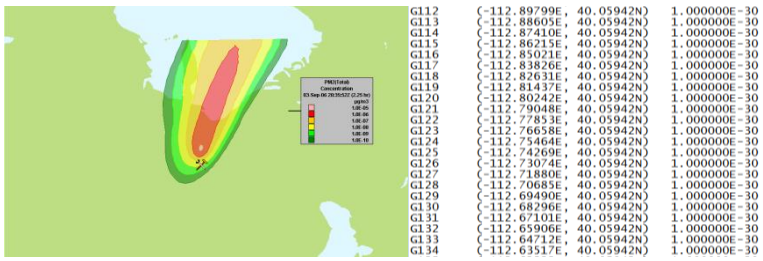
HPAC (Terrain, source)

HPAC uses internal terrain data (has a DEM file to approximate elevation changes), land cover data, and user defined or internal historic weather data to model dispersion. Since HPAC has a global internal terrain and land-cover there is no need to look for these files on the web. The main purpose of the software is to simulate NBC type threats but the software can also model generic particulate of gas releases. After

release location is selected, the user can select what type of pollutant to model, gas, liquid, particle, or aerosol. Then the user would specify amount released in µg per second and the duration of the release.

HPAC (Output)

HPAC like HYSPLIT can generate various outputs based on users preferences but the most useful outputs are graphical and text outputs. The plume concentration will be in the same units as used for input whether it is in micrograms, milligrams or kilograms per meter cubed. Graphical output is created by plotting the concentration contours based on predefined concentration values and the text out is created by user defined receptor grid where HPAC calculated concentration values for those points.



G112	(-112.89799E, 40.05942N)	1.000000E-30
G113	(-112.88605E, 40.05942N)	1.000000E-30
G114	(-112.87410E, 40.05942N)	1.000000E-30
G115	(-112.86215E, 40.05942N)	1.000000E-30
G116	(-112.85021E, 40.05942N)	1.000000E-30
G117	(-112.83826E, 40.05942N)	1.000000E-30
G118	(-112.82631E, 40.05942N)	1.000000E-30
G119	(-112.81437E, 40.05942N)	1.000000E-30
G120	(-112.80242E, 40.05942N)	1.000000E-30
G121	(-112.79048E, 40.05942N)	1.000000E-30
G122	(-112.77853E, 40.05942N)	1.000000E-30
G123	(-112.76658E, 40.05942N)	1.000000E-30
G124	(-112.75464E, 40.05942N)	1.000000E-30
G125	(-112.74269E, 40.05942N)	1.000000E-30
G126	(-112.73074E, 40.05942N)	1.000000E-30
G127	(-112.71880E, 40.05942N)	1.000000E-30
G128	(-112.70685E, 40.05942N)	1.000000E-30
G129	(-112.69490E, 40.05942N)	1.000000E-30
G130	(-112.68296E, 40.05942N)	1.000000E-30
G131	(-112.67101E, 40.05942N)	1.000000E-30
G132	(-112.65906E, 40.05942N)	1.000000E-30
G133	(-112.64712E, 40.05942N)	1.000000E-30
G134	(-112.63517E, 40.05942N)	1.000000E-30

Figure 16: Example output from HPAC (graphical and text)

Learning Curve

Each software takes different amount of time to learn how to use effectively, therefore not all of the software is recommended to be used in a deployed environment. ALOHA is the simplest software to learn. ALOHA works on most Windows and Macintosh computers. The software is free; it can be downloaded and installed on any computer system. The user's manual provides a good description on ALOHA's capabilities and provides some example scenarios for novice users. The software is easy and intuitive to use. The simplicity of the software is its main advantage. Some

drawbacks to the software is that ALOHA can only model gases that are in its inventory, terrain is assumed to be flat, weather inputs are simple and do not represent reality, and source emission can only be modeled up to one hour. If the user needs only a quick and rough estimate of downwind concentration of a particular gas this software is the best choice. If the user needs to determine what pollutants people were exposed to for an extended period of time with complex weather and terrain conditions the user should select another dispersion modeling software. The dispersion concentration values that are calculated by ALOHA are only good for early responders for various gas leaks.

AERMOD is EPA preferred method for modeling pollutant dispersion. The atmospheric dispersion model has been in development for a long time and has shown to perform well for many types of source release and weather conditions. However, the software, which is written in FORTRAN currently has issues with Windows 64-bit operating systems. To run the dispersion model the user has to do a lot of preparation work to create various input files for AERMOD executable to run. All of the input files must be edited in text or notepad where the user has great potential for making numerous errors which will create runtime errors when the user tries to run the dispersion model. To use dispersion model the user needs to be an expert on how to create these input files, which will take a significant time to learn. This dispersion model in not recommended to be used in AOR by bioenvironmental engineer due to amount of time it would take the person to learn how to use the software correctly and effectively. Since the dispersion model is well established the software should not be ruled out entirely. AERMOD version that is downloaded from EPA comes in this form, if a user has reach back capability to an expert in AERMOD this software should be used for local dispersion

calculations. Also, various environmental companies like Lakes Environmental (http://www.weblakes.com/) or Breeze (http://www.breeze-software.com/default.aspx) sell their version of AERMOD with a GUI which enable the user to create a dispersion model by graphically creating input files. Theses licensed versions of AERMOD sell from $1,200 to $1,600 and some require yearly license renewal fees. Therefore, if the user has the funds he or she can choose to purchase this software with a GUI which could be easier to use then EPA version of AERMOD.

HYSPLIT dispersion modeling software is meant to be used for regional scale (10-50 km range) releases therefore, it might not be appropriate to use this software in AOR, this due to the availability of downloaded weather data. High resolution weather data is only available for certain regions like North America and low resolution weather is available worldwide. Running dispersion model with low resolution weather data for a small grid size are will produce inaccurate results. To improve dispersion the user can enter basic weather data into HYSPLIT but the user will require more than basic understanding of the software. HYSPLIT users guide provides adequate information on the use of the software but some key details are left out therefore the user will have to perform various web searches to get a more complete understating of the software. Since this software is free, comes with a GUI, requires only basic understanding of pollutant dispersion, weather, source of emission it is recommended to be used in a deployed environment by a bioenvironmental engineer.

HPAC dispersion modeling software is intended for NBC releases but works well for generic particulate matter and gas source releases as well. It works for short and long or regional range dispersion. HPAC also has more flexibility with user weather inputs.

The user can input the location, altitude, time, temperature, wind direction, wind speed, and other values. The user's guide is approximately 900 pages but some items are not covered as well as should be therefore the user will have to use online help to get information that is not covered. The software is takes more time to learn than HYSPLIT but less time than AERMOD. Since this is DTRA software, various DOD agencies use this software and can provide assistance as needed. Therefore, because of the flexibility of this software to model different dispersion scenarios, flexible weather entry options, and moderate learning curve this software should be used whenever HYSPLIT is not applicable.

To summarize, ALOHA should be the first choice dispersion modeling software for bioenvironmental engineer for gas release scenarios in a deployed environment. HYSPLIT should be chosen second because it can model gas and particle dispersion and does not require a lot of time to learn. But the software primary use is for regional dispersion and the user should be aware of that fact. HPAC should be selected after HYSPLIT because the software takes significant time to understand how to use properly. The software main intent is for NBC releases and not for open or closed burn scenarios. AERMOD dispersion modeling software is not recommended for use in a deployed environment because learning how to use the software is too time consuming. Also setting up and running the model takes significant amount of time. If the user can get the funds to purchase the software from for profit companies with a GUI then this modeling software should be at the top of the list because AERMOD dispersion model has been extensively tested and performs well in many dispersion scenarios.

Appendix C: Waste Characterization and Weather Data

Deployed Waste Composition

Typical U.S. municipal solid waste composition is 28.2% paper, 14.1% food scraps, 13.7% yard trimmings, 12.3% plastics, 8.6% metals, 8.3% rubber, leather, and textiles, 6.5% wood, 4.8% glass, and 3.5% other (EPA, 2009). Typical waste in a deployed environment may consist of plastic, styrofoam, and food from dining facilities; discarded electronics; shipping materials such as wooden pallets and plastic wrap; appliances; and other items such as mattresses, clothing, tires, metal containers, and furniture (Trimble, 2010).

Waste Characterization

A notional deployed waste composition, based on previous surveys and expert knowledge is shown in Table (CDR Hardt, Naval Medical Research Unit - Dayton). This composition includes plastics, industrial waste, construction debris, and food slop that are characteristic at most large deployed locations. It is noted that waste composition can vary depending on location, number of personnel and other factors.

Table 11: Deployed Waste Composition

Deployed Waste Composition			
Plastics (10%)		**Misc. Combustibles (75%)**	
PETE	4.50%	Fabrics, synthetic	5.00%
HDPE	0.50%	Fabrics, natural	10.00%
PP	1.50%	Canvas, military	2.50%
PVC	1.00%	Cardboard	7.50%
PS	1.50%	Paper	22.50%
PU (foams)	0.50%	Rubber	2.50%
ABS (electronics)	0.50%	Wet food waste (slop)	22.50%
		Oils and greases	2.50%
Wood (6%)		**Dunnage (5%)**	
Treated (pallets)	3.00%	Glass	3.00%
Untreated	3.00%	Building Materials	2.00%
Metals (4.0%)			
Aluminum/Tin	2.00%		
Iron/Steel	1.00%		
Copper Wire, Insul.	1.00%		

Waste characterization was performed on residential waste and commercial waste on two separate days to find out how different our waste composition was from the deployed waste. Residential solid waste which was delivered on 26-Sep-11 was deposited in a long pile approximately 68 feet long, 10 feet wide and 3 feet high. The pile was sectioned into 16 different sections where 3 random sections were chosen as samples. The samples were collected by a skid steer and moved onto a large plastic sheet where separation was conducted. Waste was sorted into five primary groups, plastics, wood, miscellaneous combustibles and dunnage. Each main group was sorted into multiple subgroups. Plastics were resorted into Polyethylene, Polypropylene, Polyvinylchloride, and others. Miscellaneous combustibles were sorted into clothes, paper, yard waste, food waste, and others. Each waste component was weighed individually to produce waste composition. After weighing, the waste was returned to its original pile. Commercial waste was sorted in a similar manner.

Table 12: Residential Waste Composition

Residential Waste Composition				
Plastics (20%)			**Misc. Combustibles (62%)**	
Polyethylene Terephthalate (PETE) (Class 1 plastics, clear water bottles)	2.23%		Paper (cardboard, mixed paper, boxboard, etc.)	36.88%
High-Density Polyethylene (HDPE) (Class 2 plastics, milk jugs)	2.03%		Clothes & Fabric	3.85%
Polypropylene (PP) (Class 5 plastics, soda cups, yogurt boxes, syrup bottles, prescription bottles)	1.32%		Yard waste	5.67%
PVC (Class 3 plastics, all kinds of pipes and tiles)	0.00%		Food waste/Diapers	15.81%
Polystyrene (PS) (Class 6 plastics, Styrofoam, disposable coffee cups ,plastic food boxes, plastic cutlery, packing foam and peanuts)	1.22%			
Polycarbonate (Class 7 plastics (other) CDs/DVDs, baby bottles, large water bottles)	1.22%			
Appliances (plastics & metals (coffee pot)	2.63%			
Low-Density Polyethylene (LDPE) (Class 4 plastics, trash bags, plastic cling wrap, sandwich bags)	4.05%			
Misc. Plastics	5.88%			
Wood (10.3%)			**Dunnage (0.4%)**	
Pallets	10%		Glass	0.41%
Metals (6.4%)				
Aluminum cans	3.44%			
Steel Cans	3.04%			

Table 13: Commercial Waste Composition

Commercial Waste Composition				
Plastics (12%)			**Misc. Combustibles (60%)**	
Polyethylene Terephthalate (PETE) (Class 1 plastics, clear water bottles)	3.70%		Mixed Paper/boxboard	16.98%
High-Density Polyethylene (HDPE) (Class 2 plastics, milk jugs)	1.23%		Cardboard	31.33%
Polypropylene (PP) (Class 5 plastics, soda cups, yogurt boxes, syrup bottles, prescription bottles)	0.62%		Clothes & Fabric	0.31%
PVC (Class 3 plastics, all kinds of pipes and tiles)	0.00%		Yard waste	7.41%
Polystyrene (PS) (Class 6 plastics, Styrofoam, disposable coffee cups ,plastic food boxes, plastic cutlery, packing foam and peanuts)	0.46%		Food waste/Diapers	4.32%
Polycarbonate (Class 7 plastics (other) CDs/DVDs, baby bottles, large water bottles)	0.00%			
Foam Insulation/Packing Foam	1.08%			
Low-Density Polyethylene (LDPE) (Class 4 plastics, trash bags, plastic cling wrap, sandwich bags)	4.17%			
Misc. Plastics	1.08%			
Wood (12%)			**Dunnage (1%)**	
Pallets/Lumber	12%		Glass	1.08%
Metals (13%)			**E-waste (2%)**	
Aluminum cans	0.46%		Ballasts & battery	1.54%
Steel (cans/wire/other)	11.11%			
Copper	1.39%			

Weather Data Used in Models

EPA collected the weather data for the duration from 26 September 2011 to 8 October 2011. Temperature, humidity, wind speed and direction were recorded in a one-minute increment. Weather used in ALOHA, HYSPLIT and HPAC was averaged at one hour increments. The table below shows weather data used in the models during open burns. Stability and mixing heights were attained from NOAA website http://ready.arl.noaa.gov/READYametus.php.

Table 14: 30 Sep 11 Weather Data

30-Sep-11							
MST	UTC	Temperature (°C)	Wind Speed (m/s)	Direction From	Humidity (%)	Mixing Height (m AGL)	Stability
1530	2130	28.0	3.7	315.4	21.3	2914	3
1630	2230	28.0	2.4	310.1	22.1	3341	3
1730	2330	26.6	2.4	304.9	20.6	3767	3
1830	0030	26.0	1.5	266.9	21.1	3292	4
1930	0130	24.4	1.7	105.7	22.7	1997	4

Table 15: 1 Oct 11 Weather Data

1-Oct-11							
MST	UTC	Temperature (°C)	Wind Speed (m/s)	Direction From	Humidity (%)	Mixing Height (m AGL)	Stability
1530	2130	27.1	5.9	144.8	21.6	2387.0	2
1630	2230	27.4	6.7	175.1	21.2	2802.2	2
1730	2330	26.8	6.9	157.1	21.6	3249.4	3
1830	0030	25.5	5.1	169.5	23.9	1563.8	3
1930	0130	---	---	---	---	565.9	3
2030	0230	22.5	4.9	139.9	29.8	50	4

Table 16: 2 Oct 11 Weather Data

2-Oct-11							
MST	UTC	Temperature (°C)	Wind Speed (m/s)	Direction From	Humidity (%)	Mixing Height (m AGL)	Stability
1730	2330	25.8	4.4	117.4	20.9	2226.59	3
1830	0030	25.3	3.3	139.1	21.2	1355.92	3
1930	0130	23.7	3.1	139.5	24.0	485.245	3
2030	0230	22.6	3.2	156.5	25.5	50	4
2130	0330	---	---	---	---	50	5
2230	0430	---	---	---	---	50	4
2330	0530	---	---	---	---	50	4

Table 17: 3 Oct 11 Weather Data

3-Oct-11							
MST	UTC	Temperature (°C)	Wind Speed (m/s)	Direction From	Humidity (%)	Mixing Height (m AGL)	Stability
1230	1830	25.6	6.5	138.8	25.1	2000	3
1330	1930	27.4	7.1	156.0	20.1	2200	3
1430	2030	26.4	5.7	197.0	20.9	2400	4
1530	2130	26.6	5.5	171.3	19.2	2500	4
1630	2230	---	---	---	---	2600	4

Appendix D: Additional Results

Table 18: 30 Sep Model Prediction to Ground Comparison

Model	GL	FB	MG	NMSE	VG	FAC2
ALOHA CO_2	S	2.00	N/A	N/A	N/A	0
	M	2.00	N/A	N/A	N/A	0
	L	2.00	N/A	N/A	N/A	0
HPAC CO_2	S	1.96	1.11E+02	1.09E+02	4.E+09	8.90E-03
	M	1.98	2.02E+02	2.01E+02	2.E+12	4.84E-03
	L	1.95	75.60	73.61	2.E+08	1.24E-02
HPAC $PM_{2.5}$	S	1.89	35.62	33.65	3.E+05	2.81E-02
	M	1.97	1.14E+02	112.10	6.E+09	8.76E-03
	L	1.85	24.90	22.94	3.E+04	4.02E-02
HYSPLIT CO_2 SW	S	2.00	N/A	N/A	N/A	0
	M	2.00	N/A	N/A	N/A	0
	L	2.00	N/A	N/A	N/A	0
HYSPLIT CO_2 DW	S	-0.29	0.75	0.08	1.09	1.34
	M	0.31	1.37	0.10	1.10	0.73
	L	-0.62	0.53	0.42	1.50	1.89
HYSPLIT $PM_{2.5}$ SW	S	2.00	N/A	N/A	N/A	0
	M	2.00	N/A	N/A	N/A	0
	L	2.00	N/A	N/A	N/A	0
HYSPLIT $PM_{2.5}$ DW	S	-1.44	0.16	4.29	26.71	6.13
	M	-0.63	0.52	0.44	1.54	1.92
	L	-1.60	0.11	7.02	119.34	8.91

Table above shows FB, MG, NMSE, VG, and FAC2 for all 3 models used for $PM_{2.5}$ and CO_2. All three models performed poorly with surface weather as input. ALOHA and HYSPLIT models missed ground points entirely while HPAC predicted extremely small values. HYSPLIT performed within the accepted guidelines for good model with CO_2 as a source and only predicted the concentration of $PM_{2.5}$ of the center ground point. Since 1hr averaged wind speed and direction were used, the models missed

the ground points. In reality wind direction changed from ENE to WSW in the 3hr sampling period. Average wind speed over the sampling period was 2.9 m/s, wind direction was from NNW, and stability was neutral.

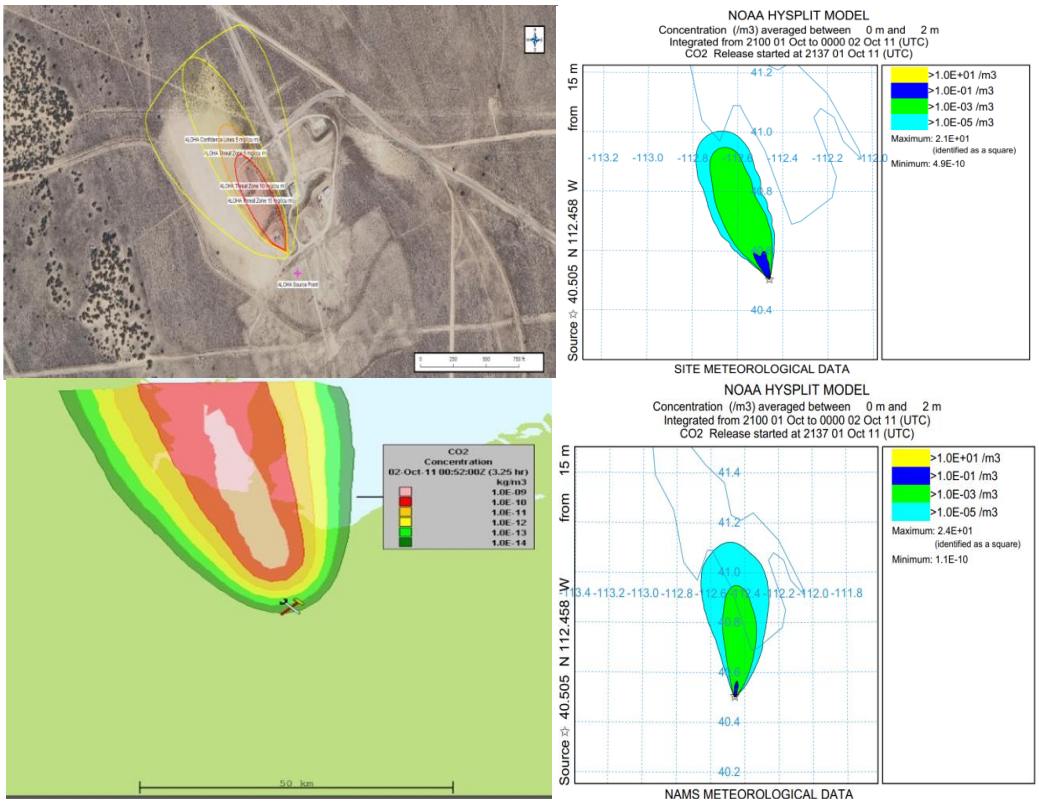


Figure 17: 1 Oct Contours, ALOHA (Top Left), HYSPLIT SW (Top Right), HPAC (Bottom Left), HYSPLIT DW (Bottom Right)

From the visual comparison of HPAC, ALOHA and HYSPLIT models show the main direction the concentration to be from South to SSE for the surface weather data during the sampling time. Direction is primarily from the South for the downloaded weather data. Two source release heights were used, zero and 15 meters AGL, but the difference again was not noticeable except in ALOHA.

Table 19: 1 Oct Model Prediction to Ground Comparison

Model	GL	FB	MG	NMSE	VG	FAC2
Aloha 0 m Z CO_2	S	-1.87	12.08	-12.51	1.30E+05	30.94
	M	1.53	46.63	48.37	5.80E+01	0.13
	L	0.61	78.01	81.25	1.50E+00	0.53
Aloha 15 m Z CO_2	S	2.00	N/A	N/A	N/A	0
	M	2.00	N/A	N/A	N/A	0
	L	1.98	1.90E+02	1.88E+02	9.E+11	1.58E-02
HPAC CO_2	S	2.00	1.42E+08	1.42E+08	1.E+153	6.54E-07
	M	2.00	1.57E+06	1.57E+06	3.E+88	2.55E-07
	L	2.00	1.03E+07	1.03E+07	2.E+113	1.55E-07
HPAC $PM_{2.5}$	S	2.00	9.10E+06	9.10E+06	3.E+111	1.10E-07
	M	2.00	2.07E+07	2.07E+07	2.E+123	4.84E-08
	L	2.00	1.85E+07	1.85E+07	4.E+121	5.40E-08
HYSPLIT CO_2 SW	S	2.00	N/A	N/A	N/A	0
	M	2.00	N/A	N/A	N/A	0
	L	2.00	N/A	N/A	N/A	0
HYSPLIT CO_2 DW	S	-0.41	0.66	0.18	1.19	1.52
	M	0.54	1.74	0.31	1.36	0.58
	L	0.98	2.93	1.27	3.17	0.34
HYSPLIT $PM_{2.5}$ SW	S	2.00	N/A	N/A	N/A	0
	M	2.00	N/A	N/A	N/A	0
	L	2.00	N/A	N/A	N/A	0
HYSPLIT $PM_{2.5}$ DW	S	0.72	2.12	0.59	1.75	0.47
	M	1.33	4.94	3.14	12.81	0.20
	L	1.28	4.55	2.77	9.94	0.22

Table 19 shows FB, MG, NMSE, VG, and FAC2 for all 3 models used for $PM_{2.5}$ and CO_2. At 15 m AGL source release HPAC and ALOHA and HYSPLIT under-predicted ground concentrations with surface weather as input. ALOHA at 0 m over-predicted concentration at closest point to the source and under-predicted the middle and far points. HYSPLIT with downloaded weather predicted CO_2 ground concentration

within acceptable parameters for close and middle points. Again, HYSPLIT under-predicted $PM_{2.5}$ ground concentration.

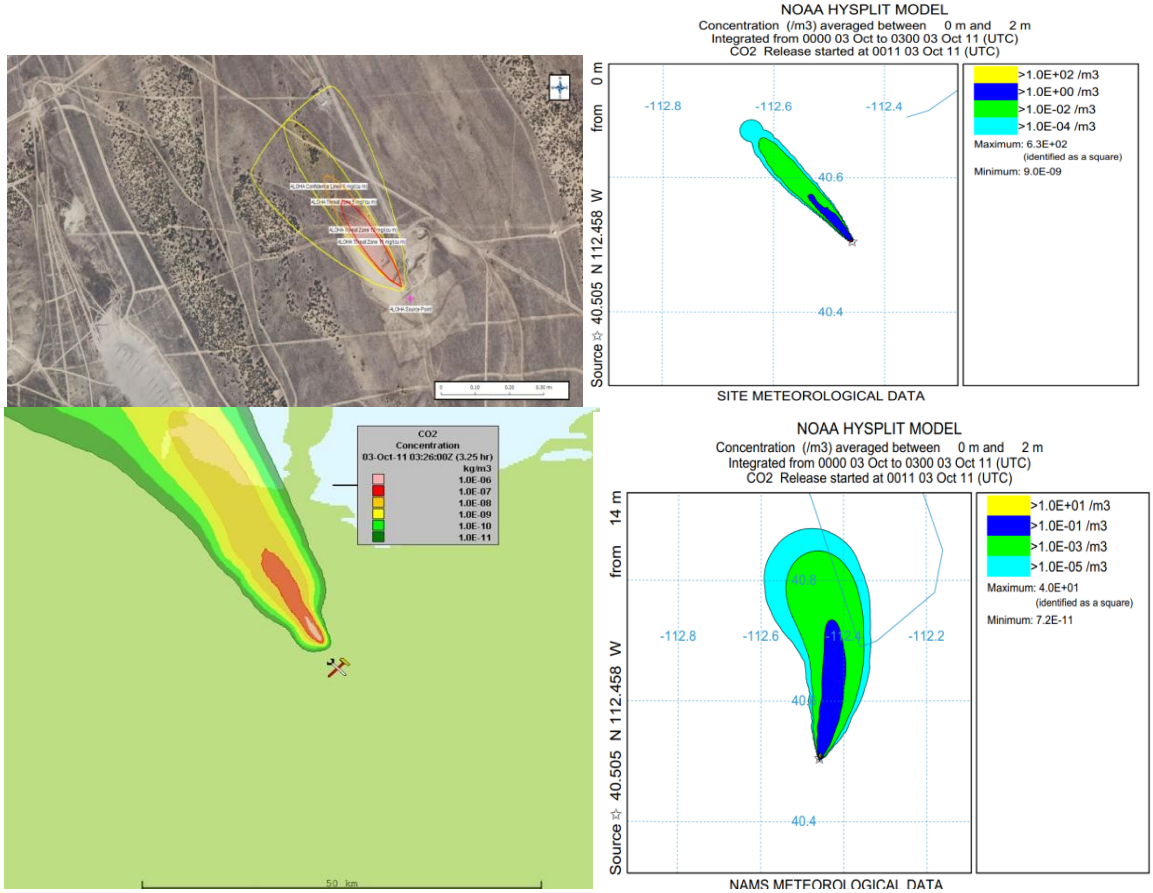


Figure 18: 2 Oct Contours, ALOHA (Top Left), HYSPLIT SW (Top Right), HPAC (Bottom Left), HYSPLIT DW (Bottom Right)

Figure 15 shows graphical outputs from their respective models. From the visual comparison of HPAC, ALOHA and HYSPLIT models show the main direction the concentration to be from SE for the surface weather data during the sampling time. Direction is primarily from the South to SSW for the HYSPLIT downloaded weather data. Two source release heights were used, zero and 14 meters AGL, but the difference again was not noticeable in all models.

Table 20: 2 Oct Model Prediction to Ground Comparison

Model	GL	FB	MG	NMSE	VG	FAC2
Aloha CO2	S	2.00	N/A	N/A	N/A	0
	M	2.00	1.35E+03	1.35E+03	3.72E+22	7.40E-04
	L	2.00	N/A	N/A	N/A	0
HPAC CO2	S	2.00	N/A	N/A	N/A	0
	M	2.00	N/A	N/A	N/A	0
	L	2.00	N/A	N/A	N/A	0
HPAC PM2.5	S	2.00	N/A	N/A	N/A	0
	M	2.00	N/A	N/A	N/A	0
	L	2.00	N/A	N/A	N/A	0
HYSPLIT CO2 SW	S	2.00	N/A	N/A	N/A	0
	M	2.00	N/A	N/A	N/A	0
	L	2.00	N/A	N/A	N/A	0
HYSPLIT CO2 DW	S	1.36	5.26	3.45	15.71	0.19
	M	0.58	1.81	0.36	1.42	0.55
	L	-0.93	0.36	1.11	2.77	2.74
HYSPLIT PM2.5 SW	S	2.00	N/A	N/A	N/A	0
	M	2.00	N/A	N/A	N/A	0
	L	2.00	N/A	N/A	N/A	0
HYSPLIT PM2.5 DW	S	1.44	6.09	4.25	26.12	0.16
	M	1.20	4.03	2.28	6.98	0.25
	L	-1.81	0.05	18.18	8.22E+3	20.13

Comparison of ground concentration and predicted values for 2nd October is summarized in Table 20. Release heights that were modeled were 14 and 0 m AGL. No models predicted ground concentrations using surface weather data as input. HYSPLIT predicted ground concentration of CO_2 for the middle point, which was approximately 90 meters away from the source using downloaded weather data. The software under-predicted the concentration for the close point and over-predicted for the farthest point.

For $PM_{2.5}$ HYSPLIT under-predicted concentration for the close and the middle ground points and over-predicted farthest point.

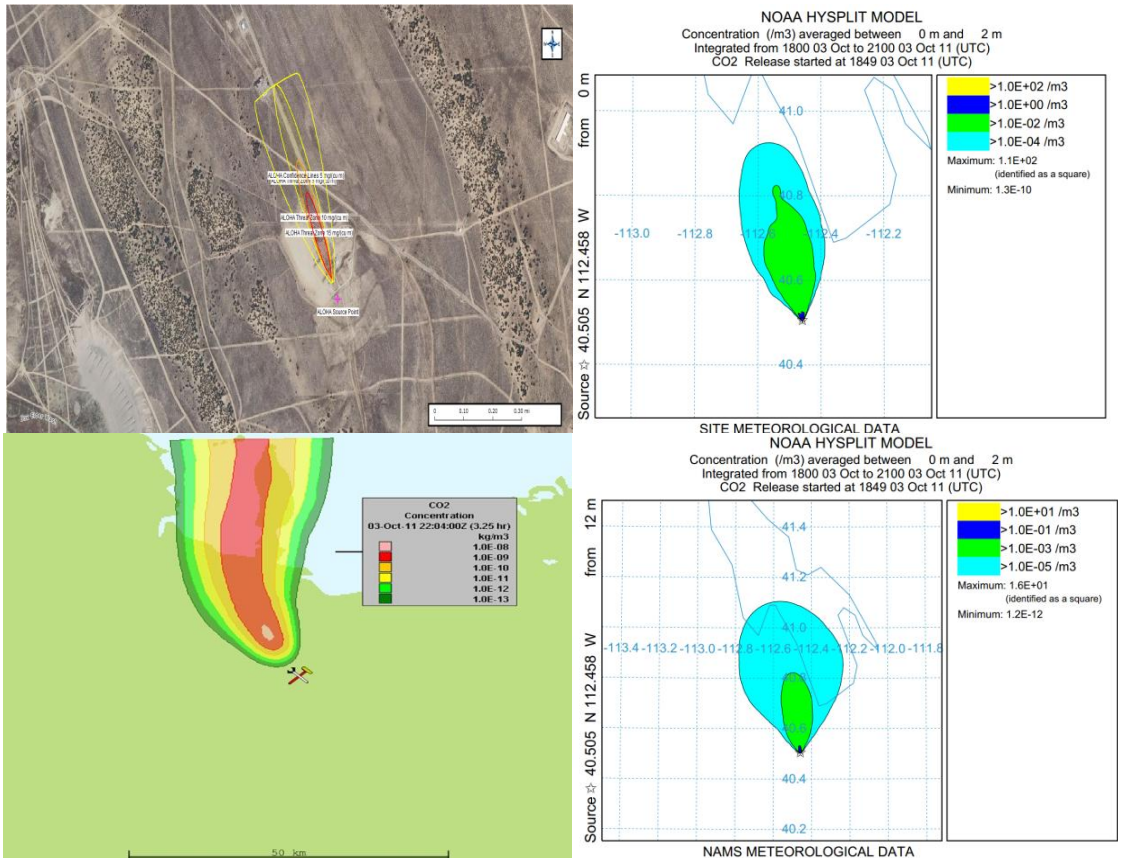


Figure 19: 3 Oct Contours, ALOHA (Top Left), HYSPLIT SW (Top Right), HPAC (Bottom Left), HYSPLIT DW (Bottom Right)

3 October model graphical outputs are shown in Figure 18. Primary wind direction during the sampling phase was from the South to SSE. Both the surface weather and the downloaded weather data show similar shape of the downwind concentration for HYSPLIT model. Average wind speed during the sampling period was 6.2 m/s.

Table 21: 3 Oct Model Prediction to Ground Comparison

Model	GL	FB	MG	NMSE	VG	FAC2
Aloha 0 m Z CO_2	S	0.25	1.29	0.07	1.07E+00	0.78
	M	1.81	19.78	17.83	7.40E+03	0.05
	L	1.91	42.40	40.42	1.25E+06	0.02
Aloha 12 m Z CO_2	S	2.00	1.34E+04	1.34E+04	1.61E+39	0.00
	M	1.94	62.01	60.03	2.50E+07	0.02
	L	1.88	31.80	29.83	1.58E+05	0.03
HPAC CO_2	S	2.00	N/A	N/A	N/A	0
	M	2.00	N/A	N/A	N/A	0
	L	2.00	N/A	N/A	N/A	0
HPAC $PM_{2.5}$	S	2.00	N/A	N/A	N/A	0
	M	2.00	N/A	N/A	N/A	0
	L	2.00	N/A	N/A	N/A	0
HYSPLIT CO_2 SW	S	1.99	7.40E+02	7.38E+02	9.02E+18	0.00
	M	1.99	3.04E+02	3.02E+02	1.57E+14	0.00
	L	1.98	2.13E+02	2.11E+02	3.10E+12	0.00
HYSPLIT CO_2 DW	S	1.68	11.69	9.78	4.23E+02	0.09
	M	1.31	4.81	3.01	11.75	0.21
	L	1.09	3.37	1.67	4.38	0.30
HYSPLIT $PM_{2.5}$ SW	S	2.00	N/A	N/A	N/A	0.00
	M	2.00	N/A	N/A	N/A	0.00
	L	2.00	N/A	N/A	N/A	0.00
HYSPLIT $PM_{2.5}$ DW	S	1.61	9.22	7.33	1.39E+02	0.11
	M	1.35	5.16	3.36	14.81	0.19
	L	0.89	2.59	0.98	2.48	0.39

Table above provides model performance for 3rd October. There was a slight difference in ALOHA models with source releases at 0 m AGL and 12 m AGL. At ground level ALOHA was able to predict ground concentration values for the nearest point to the source. All other models performed outside acceptable parameters for a good model for this day and predicted a near zero concentration values. HYSPLIT with

downloaded weather data also performed poorly and under-predicted ground concentrations for all points.

30 Sep Additional Results

Models did not perform well in detecting ground concentration values using surface weather over a 3hr sampling time. Therefore, the models have been standardized using only one hour averaged weather input, wind and direction for 30 Sep open burn to see whether models are in general agreement with each other under similar weather inputs. HYSPLIT and HPAC were imported into ArcGIS to display the results.

Figures 20-22 show the dispersion runs using 1hr averaged surface weather data for HYSPLIT, HPAC, and ALOHA, respectively. The main contours to be compared are 0.7 mg/m^3 (HYSPLIT and HPAC orange, ALOHA red), 0.1 mg/m^3 (HYSPLIT and HPAC yellow, ALOHA orange), and 0.01 mg/m^3 (HYPSLIT and HPAC green, ALOHA yellow). Since the weather direction and wind speed were the same for all models, the direction and spread of the contours should be similar across all models.

Comparing 0.7 mg/m^3 ALOHA (red) to HPAC and HYPLIT (orange) contours visually, the contour downwind distances are similar for HPAC and ALOHA. HPAC has a larger spread in its concentration (dispersion), as compared to ALOHA and HYSPLIT. By looking at the HYSPLIT contour for the same concentration value, it extends further from the source and partially reaches the mountains. Therefore, HYSPLIT over-predicts ground concentrations further downwind compared to the other two models.

Comparing 0.1 mg/m^3 ALOHA (orange) to HPAC and HYPLIT (yellow) contours visually, HYSPLIT and ALOHA have a similar plume length and spread. HPAC plume length is shorter than the other two models, but its spread is a lot larger.

Therefore, HPAC would under-predict ground concentration compared to HYSPLIT and ALOHA.

Looking closer at the last contour, 0.01 mg/m^3, there some visual differences between ALOHA (yellow), HPAC and HYSPLIT (green). The HYSPLIT contour barely reaches the peak of the mountains and maintains spread similar to its other contours. HPAC's contour goes off the visual map and is larger than the other two models. ALOHA's contour is cut off due to its ability to predict downwind concentration only up to a certain distance from the source (6.2 miles).

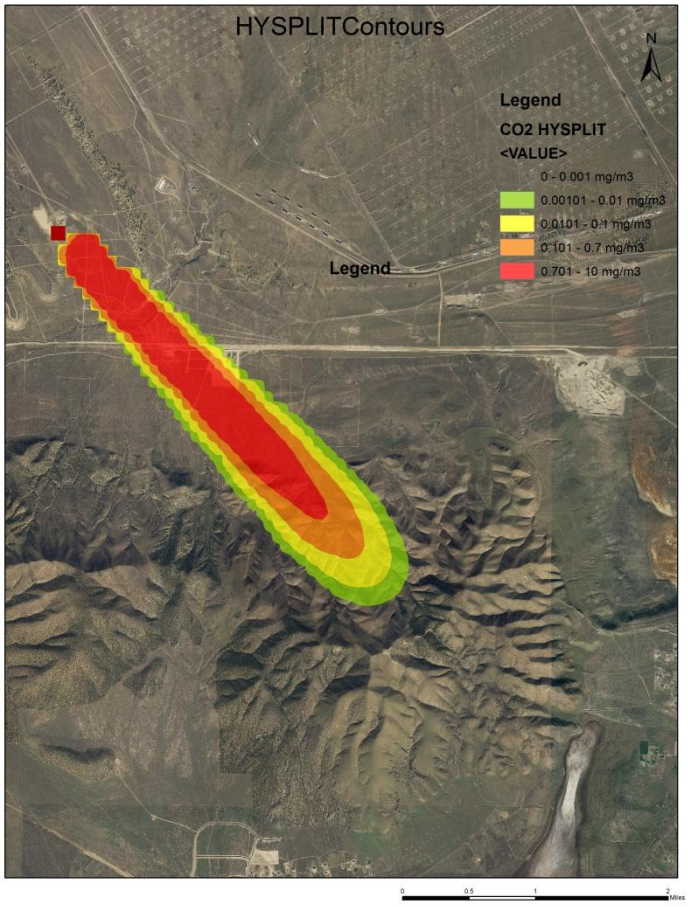


Figure 20: 30 Sep CO2 HYSPLIT 1hr avg SW

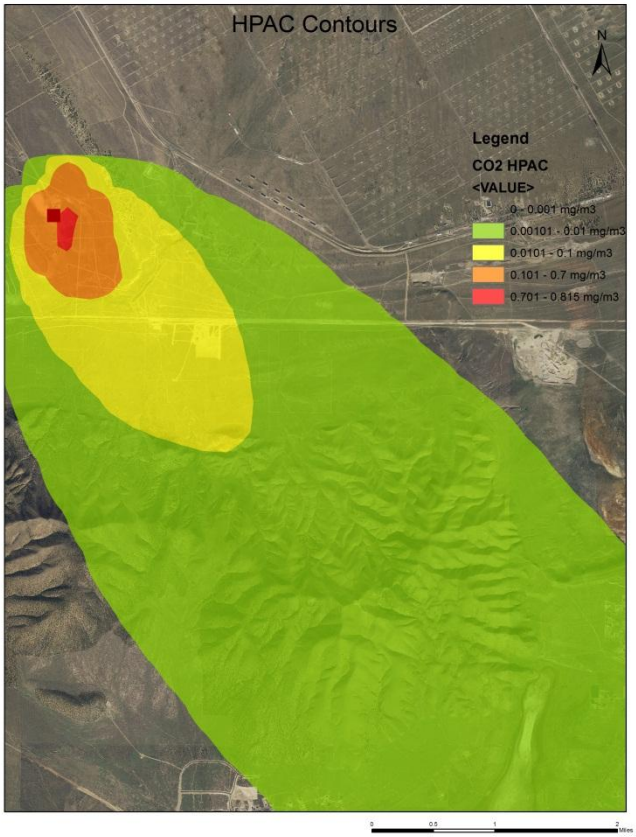


Figure 21: 30 Sep CO2 HPAC 1hr avg SW

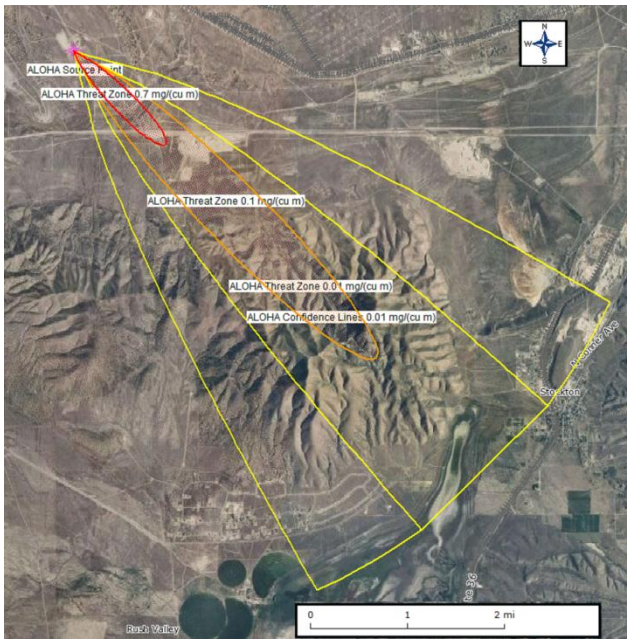
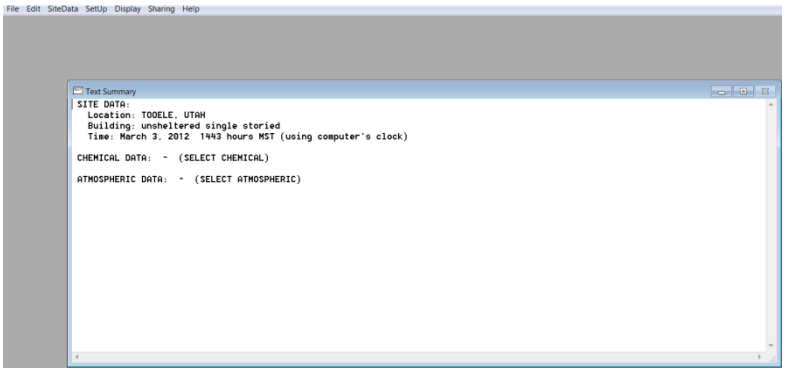


Figure 22: 30 Sep CO2 ALOHA 1hr avg SW

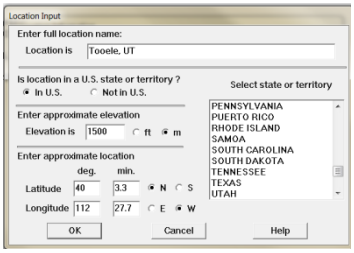
Appendix E: Procedure Log

ALOHA Procedure Log

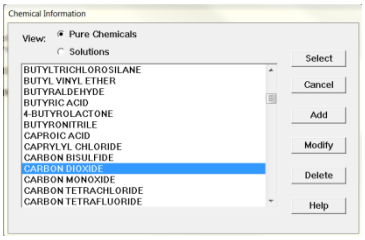
Step 1: Open ALOHA.



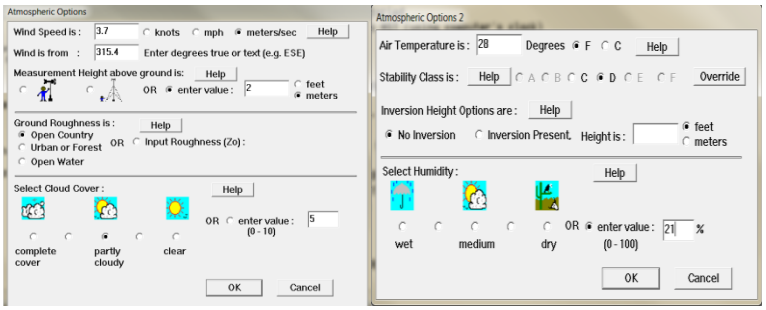
Step 2: Select a location where the source is released. Either pick a city from a drop down menu or create your own location by entering latitude and longitude.



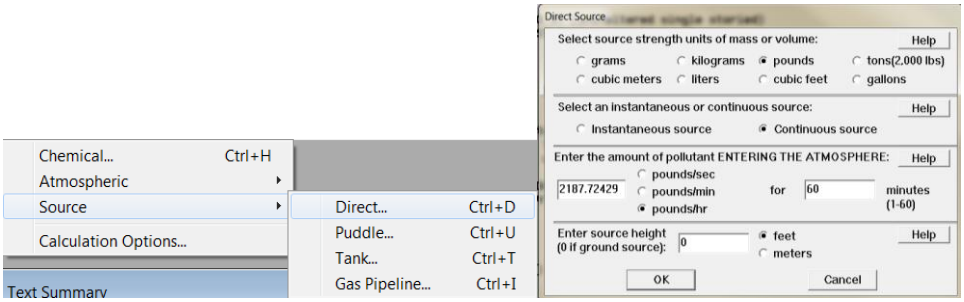
Step 3: Select a chemical from the drop down menu, CO_2 in this case. The user can modify properties if gas is not in the list.



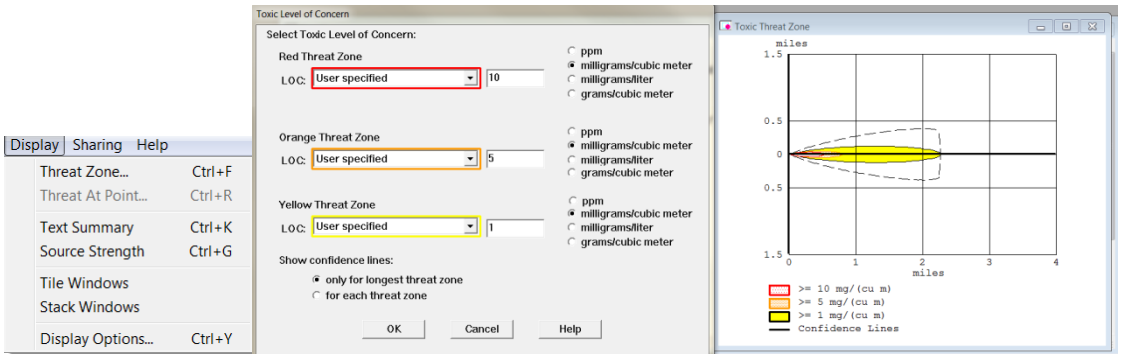
Step 4: Input weather data. Wind speed, direction, roughness length or select an option, enter cloud cover. On the second screen, enter air temperature, humidity, and inversion if known.



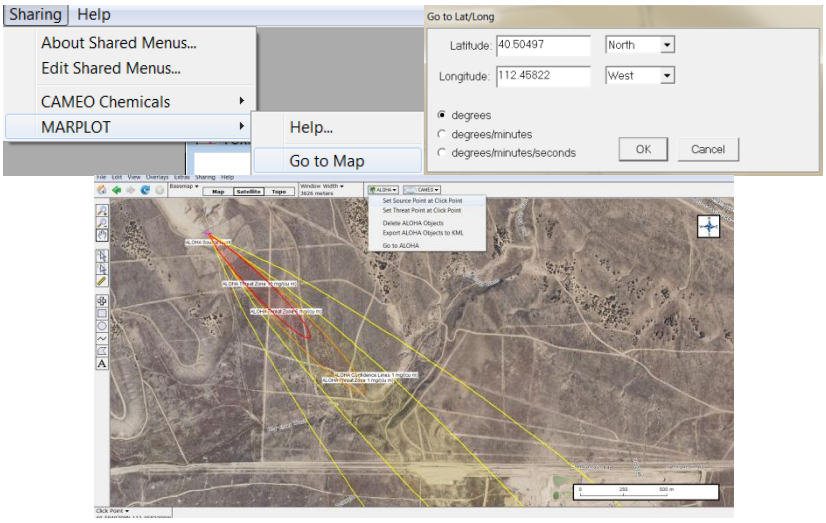
Step 5: Enter source information. Select from four options, in this case direct source. Enter amount released in lbs, kg, etc. Select continuous or instantaneous release and select release rate in mass/time. Enter release height.



Step 6: Display a threat zone for calculation. ALOHA has threat values for a particular gas that it displays or the under can enter his own contour values to display in ppm, mg/m^3, etc.



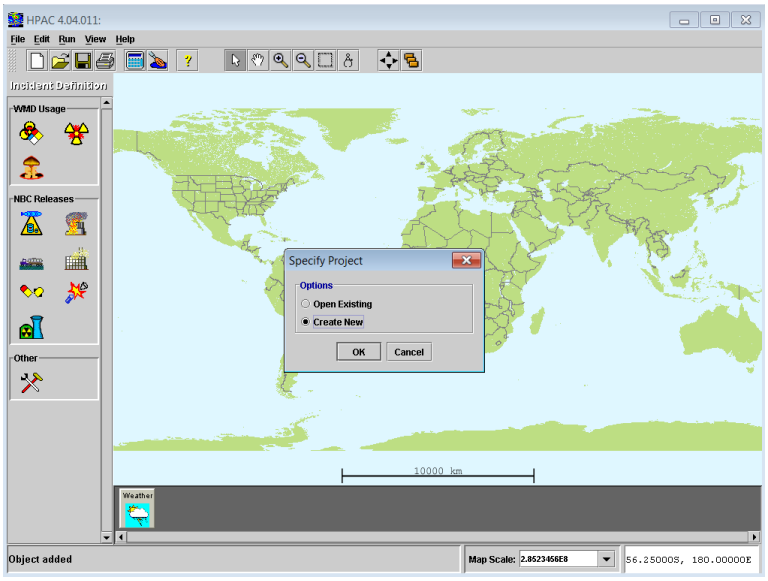
Step 7: To get a background this image needs to be exported to MARPLOT (mapping software downloaded independent). After the software opens up, right click and enter the coordinates for the source. Then go ALOHA drop down menu and set source point at click point to display on map, satellite image, or topo. Scale bar and N arrow can be added from the extras drop down menu.



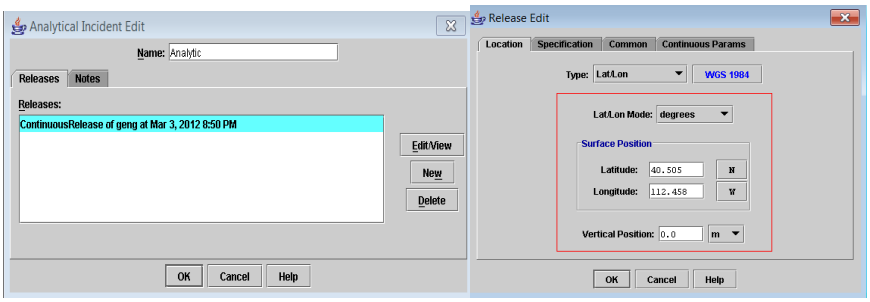
Step 8: To get concentration at a particulate coordinate point the user must go to ALOHA and select display threat at a point.

HPAC Procedure Log

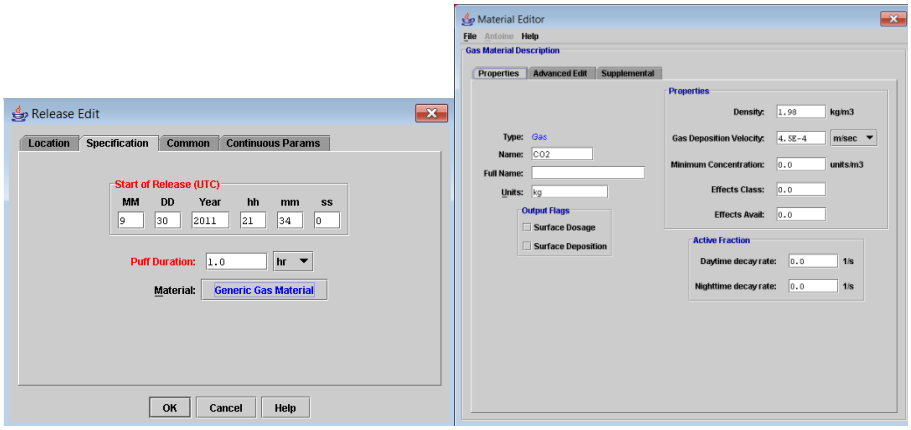
Step 1: Open HPAC and create new project.



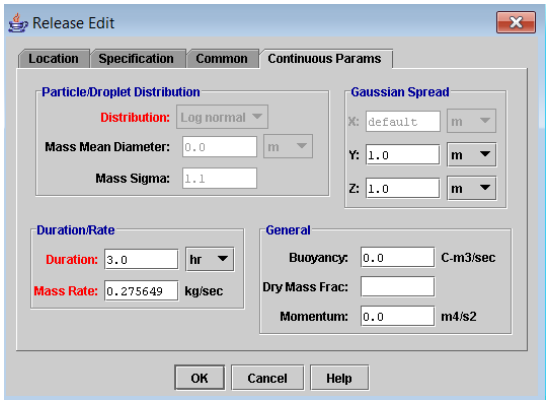
Step 2: Edit Source: Drag analytical incident (under incident definition, other option) to the map. Click edit incident and enter release location.



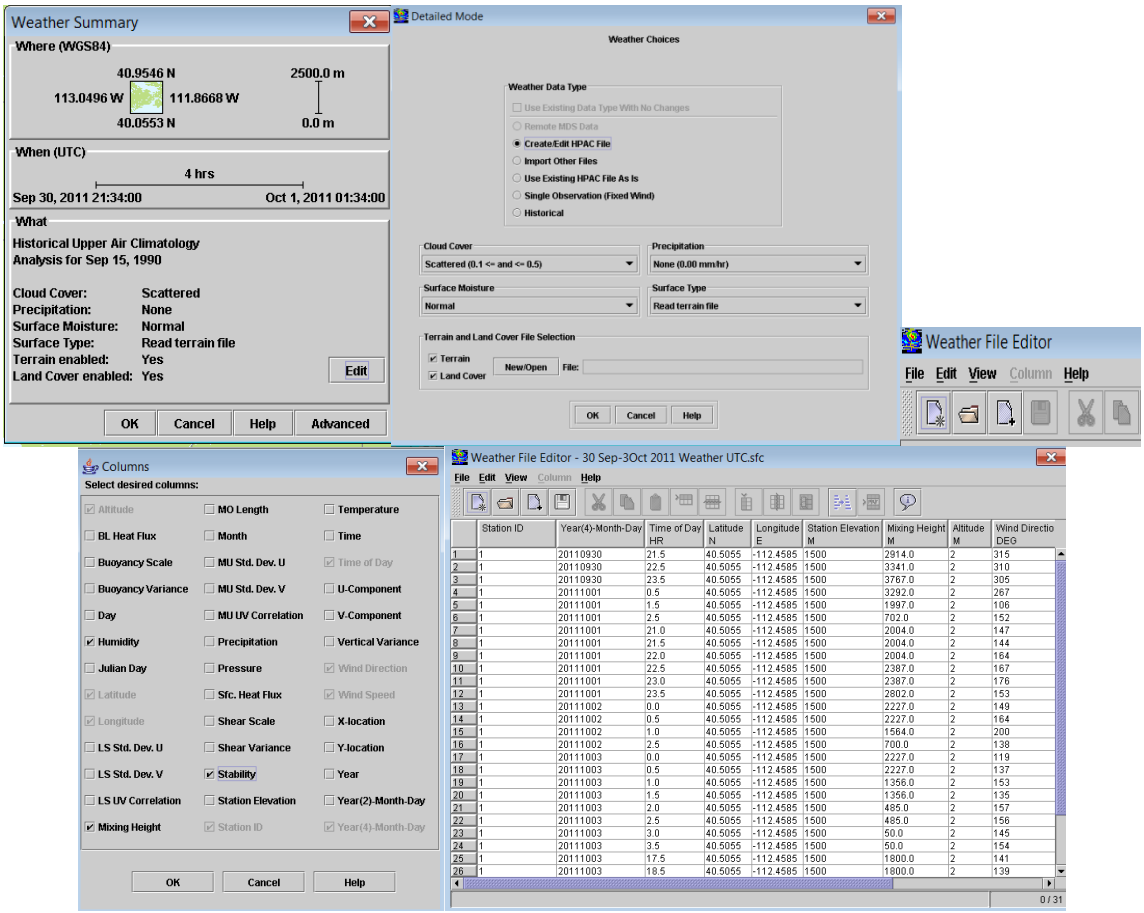
Step 3: Click on specification and enter the time of the release (UTC time). Select generic gas edit properties, enter density, gas deposition velocity, etc., and save gas properties



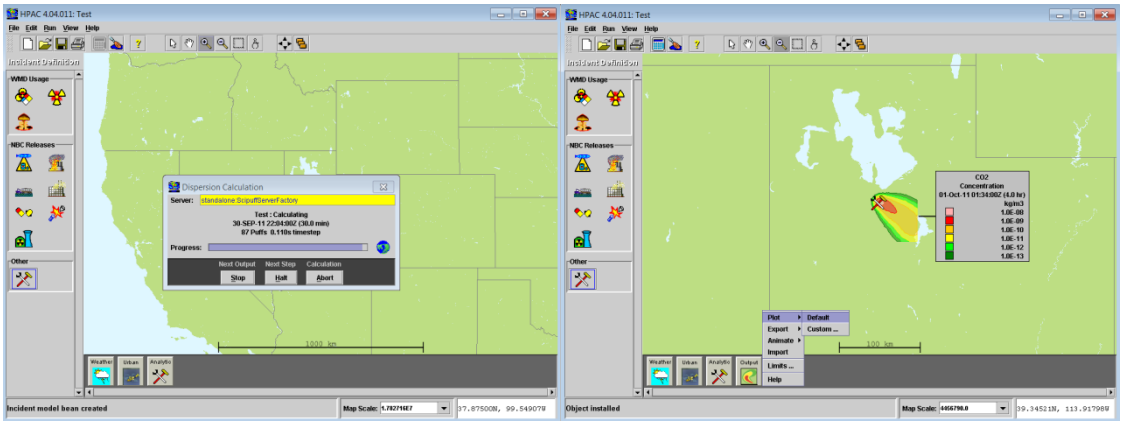
Step 4: Go back and edit continuous parameters screen. Enter the duration of the release and the mass rate in kg/sec.



Step 5: Edit weather, which is located at the bottom left corner. Select and edit HPAC file and create new weather file with selected parameters. Enter the coordinates for the weather station, time, wind speed and direction, elevation of the weather station, temperature, humidity, etc., and save the weather file.

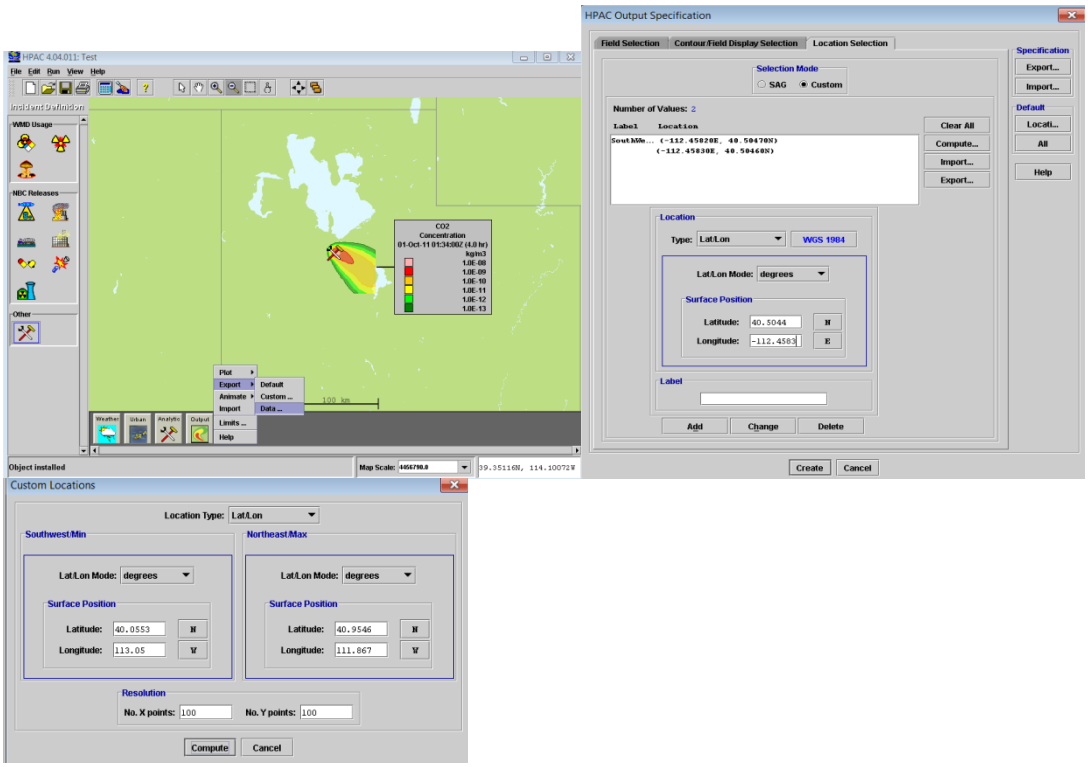


Step 6: Run dispersion model selected from the dropdown menu and display results. After the model completes running display output with default contours or define custom contours.



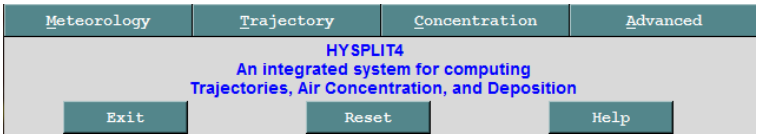
Step 7: To get concentration values for a selected location select export data from the output menu. Select the location selection tab, select custom, enter the latitude and longitude of the ground sampling station for as many stations as needed. Then click

create in the same screen and export in the .txt format to view the predicted concentration values for selected points. If the user wants to export gridded concentration values for a large domain the user can click on compute on the same screen and enter # of X points and # of Y points for a selected grid and export the .txt file the same way as for a few points.

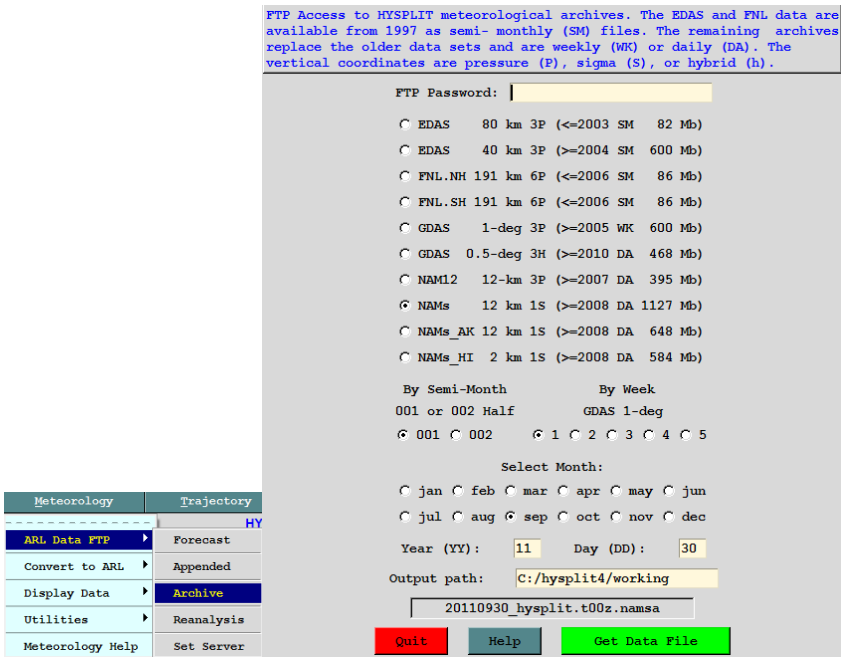


HYSPLIT Procedure Log

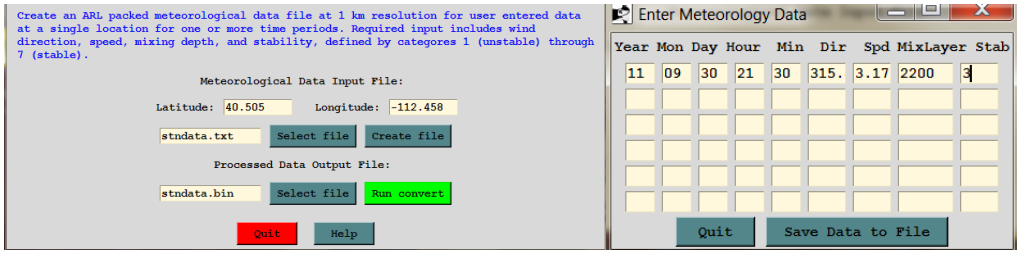
Step 1: Open HYSPLIT.



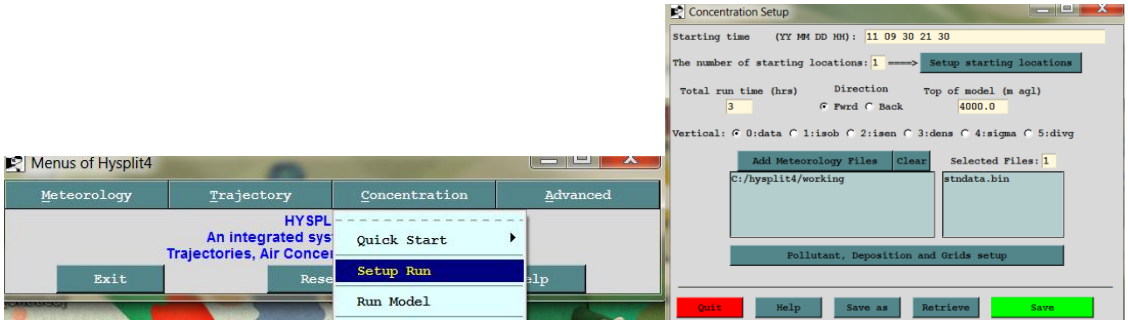
Step 2: Download weather data.

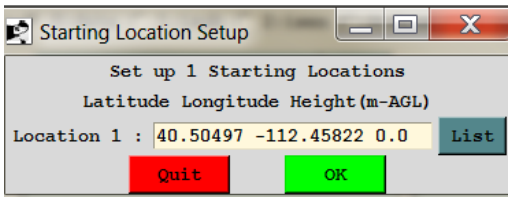


Step 3: Enter surface weather data if available. First enter weather station coordinates, then create file. Input data, time (UTC), wind direction and speed, mix layer height (AGL), and stability. Save data to file then run convert.



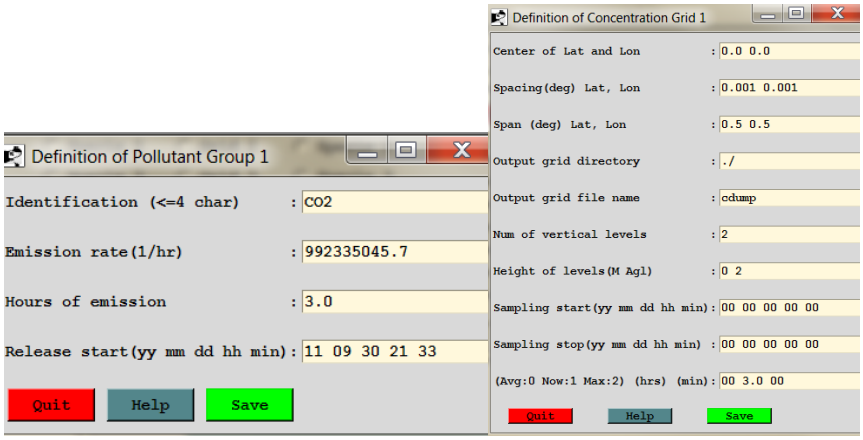
Step 3: Set up concentration dispersion run. Enter start time of the release of the pollutant in (UTC, downloaded weather data is in UTC). Set up starting position, enter latitude, longitude, and release height (can enter multiple releases), then add weather data (downloaded or user entered "stndata"), can enter multiple data files.



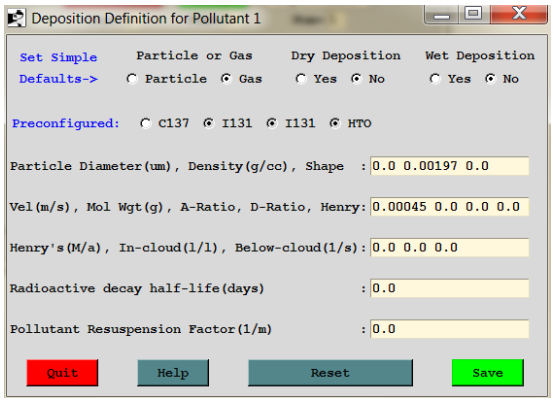


Step 4: Set up pollutant. Enter a name, emission rate in mass/hr, the duration of the release and release start time, should be the same as in previous screen.

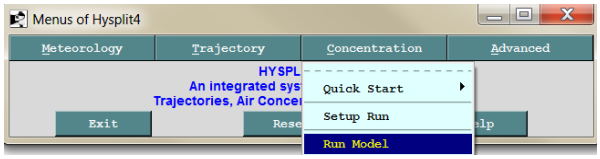
Step 5: Set up grid. "Center Lat and Lon" can be left blank which sets it to the grid to source release coordinates. Spacing of sampling points can be adjusted for more or less points. Span is to define grid size, the bigger the grid and more points will increase computational time. The model can output to multiple vertical levels, so this model will calculate concentration values for two levels at 0 and 2 m AGL. The last row sets up averaging time. First value in row is for type (0 = average, 1 = snapshot, 2 = max), second value is for averaging time, this model is set to average concentration over 3hr period.



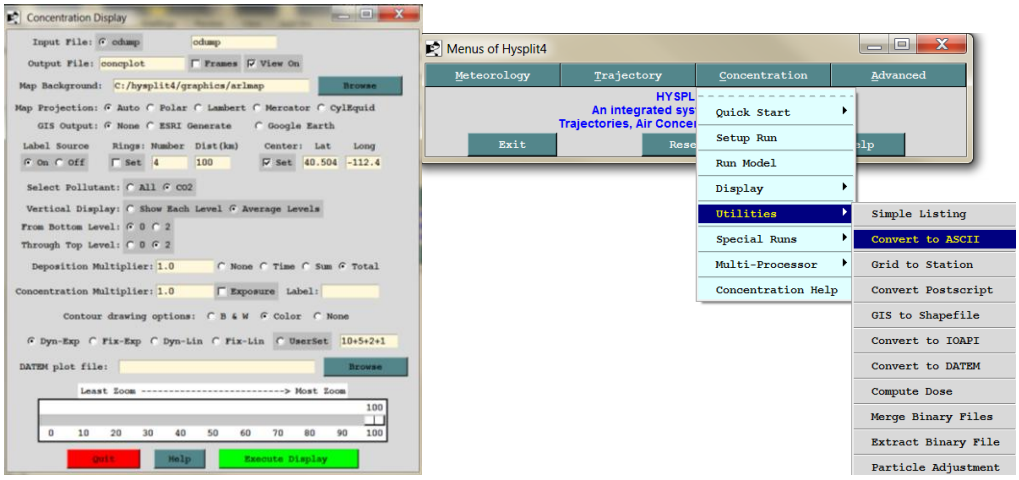
Step 6: Define gas of particle properties. Select gas or particle, enter gas density, fall velocity. The model can calculate fall velocity if molecular weight, surface reactivity, diffusivity and Henry's constants are known.



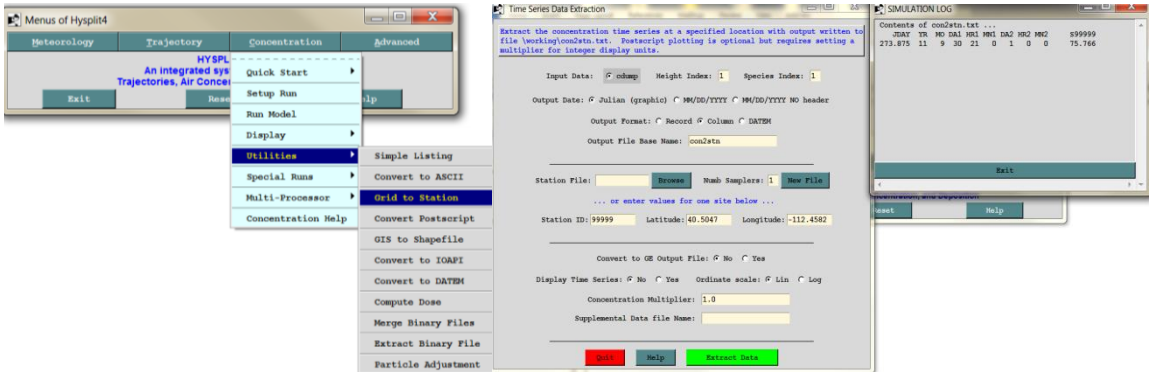
Step 7: Run model.



Step 8: Either display results graphically or create a text file with concentration values for every grid point. The user can select output to Google earth, create a shapefile for ArcGIS, or just a basic output that HYPSLIT provides. The vertical levels can be averaged or displayed individually. The user can set concentration values to be displayed or let HYSPLIT decide. To get a text output select utilities then convert to ASCII, the file will be names "cdump" and will be in working folder under HYSPLIT directory.



Step 9: HYPSLIT can also just give concentration for specific lat and lon. Go to utilities then grid to station, input ground sample lat and lon then extract data.



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13. SUPPLEMENTARY NOTES
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14. ABSTRACT
United States military forces in Iraq and Afghanistan have often used open burning of solid waste as a means to achieve volume reduction and to minimize vector borne illnesses. Assessing exposures to burn pit emissions has proven challenging, requiring significant numbers of personnel and sampling equipment. This study examined the use of three common dispersion models to determine the feasibility of using software modeling to predict short-range exposures to burn pit emissions, in lieu of sole reliance on ground sampling. Four open burn tests of municipal solid waste were conducted at Tooele Army Depot, Utah. Aerial samples were collected above the burns to determine emission factors for CO_2 and $PM_{2.5}$. Three atmospheric dispersion modeling software packages, ALOHA, HPAC, and HYSPLIT, were populated with the emission factors to determine how well they predicted ground concentrations of carbon dioxide (CO_2) and fine particulate matter ($PM_{2.5}$) at nearby monitoring stations. Results of this study show that ALOHA and HPAC did not accurately predict ground concentrations at the microscale resolution. HYSPLIT performed better than other models with more accurate predictions of CO_2 for two of the four days. This limited testing suggests that more robust ground sampling is necessary to improve assessment of model performance. Additionally, more frequent input of accurate weather data will likely improve the predictive power of these models.

15. SUBJECT TERMS
Air Dispersion Modeling, Ground Sampling, Solid Waste

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